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PRELIMINARY EVALUATION OF THE SPACE DISPOSAL OF NUCLEAR WASTE

to

MARSHALL SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION

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FOREWORD

The study described herein is a preliminary evaluation of various technical and environmental issues that are unique to the management of high-level nuclear wastes by disposal of selected components in space. Space disposal can be used in conjunction with terrestrial disposal to possibly effect a more flexible waste management system. It is an integral part of a larger evaluation program managed by NASA-Marshall Space Flight Center and included participation by Marshall Space Flight Center, ERDA, Jet Propulsion Laboratories, and Northrop Services, Inc., and should be considered only in the context of the rest of the study. This portion was conducted jointly by the Columbus and the Pacific Northwest Laboratories of Battelle Memorial Institute. This portion of the study had a major objective of determining the modifications of waste processing technology required by space disposal. It was not the responsibility of this task to evaluate the economics of space disposal.

The study made maximum utilization of ERDA information relating to the terrestrial management of high-level waste. In particular, inputs from staff at Battelle-Northwest and J. O. Blomeke of Oak Ridge National Laboratory were of special assistance. The study was scoped as a preliminary assessment of the problem in light of changing national nuclear policy, new technology, and imminent availability of the Space Shuttle since the last evaluation* of the concept. As such, it was intended that the unique processing and packaging requirements and environmental considerations of waste disposal in space be evaluated to permit: (1) a scoping or definition of the problem, (2) tentative conclusions on most major issues, and (3) identification of critical unresolved issues.

*"Feasibility of Space Disposal of Radioactive Nuclear Waste", NASA-TM-X-2911, December, 1973.

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EXECUTIVE SUMMARY

Introduction

The concept of ultimate disposal of high level nuclear waste in space has been evaluated in a preliminary manner from the viewpoints of processing spent fuel, containerization, and environmental effects of the operations. The study was not all-inclusive nor detailed; however, the concept does not appear to have any insurmountable technical problems. It is important to be aware that the assessment emphasized identification of ways in which space disposal might be different from, and an augment to, terrestrial isolation technology as currently being developed by ERDA. Each major aspect of the analysis is treated separately in following sections.

Processing

The disposal of high level waste (HLW)* in space requires the chemical processing of spent fuel elements which are assumed to be produced by a current projection of nuclear power capacity growth. In 1975, the United States had a 1365 MT reprocessing backlog and 23,204 MT of spent fuel requiring processing were projected up to and including the year 2000. The management method of the HLW needs to allow isolation of the solidified waste from man for many thousands of years. Disposal in space is a possible supplement to terrestrial disposal to rid Earth of the more objectionable components of HLW. The disposal of waste in space assumes the material to have been out of the reactor for at least 10 years. By assuming that processing of the fuel will begin by 1981, an estimate of amount of HLW that will require disposal was determined. The most optimistic case would allow 1365 MT of waste to be ready in 1985. The annual amount for disposal would rise to a value of 4062 MT in 2000.

Five different options for partitioning the waste into fractions of different relative potential hazards were explored. They are

(1) The fuel is leached from its clad and the entire dissolver solution is solidified and shipped into space.

(2) 99.5 percent of the uranium is recovered from the dissolver solution. The remaining dissolver solution is solidified and sent into space.

(3) 99.5 percent of the uranium and plutonium is recovered from the dissolver solution. The remaining dissolver solution is solidified and sent into space.

(4) 0.1 percent of the uranium and plutonium, the balance of the actinides and all the rare earths except cerium are solidified and sent into space.

(5) 99.5 percent of the uranium and plutonium and a minimum of 94 percent of the technetium are recovered from the dissolver solution. Only the technetium is sent into space.

By the use of documented chemical techniques, the above options were judged obtainable. The options gave smaller amounts of waste to be disposed of terrestrially than if partitioning were not used. The fractions of the original dissolver solution requiring space disposal for each option are shown in Table I.

*Acronyms are defined in Section 7, "Glossary".

TABLE I. WT FRACTION OF DISSOLVER SOLUTION REQUIRING SPACE DISPOSAL

Option	Fraction
1	1.0
2	0.044
3	0.035
4	0.009
5	0.0008

The waste nuclides requiring disposal could possibly be solidified into several different forms including calcines, borides, carbides, nitrides, supercalcines, coated pellets, metal matrices, or glass. Not all these forms have been developed. The technology involved in producing calcines and glasses are developed and glass is the current primary choice for the terrestrial disposal of HLW. It is very durable and restricts the movement of the waste nuclides. The total weight and volume of waste to be disposed of depends on the form the waste is solidified into. The forms all add additional weight to the various options. The amounts vary from 10 percent for nitrides to 252 percent for the glasses. Calcines add about 17 percent more weight to the waste package.

The feasibility of using solid forms other than calcines or glasses needs to be proven. The chemistry of forming these alternative materials is complex due to the complexity of the HLW chemistry itself. It is impossible to predict how the mixtures will behave under processing. Only experimental work will give the required answer.

Capital cost estimates for a processing plant required to produce the various waste options were accomplished. The reference option is Option 3 which corresponds to a near-term commercial fuel reprocessing plant. The cost factors (cost of plant/cost of reference plant) for the various options are shown in Table II.

TABLE II. ESTIMATED COST FACTORS FOR PROCESSING PLANT

Option	Cost Factor
1	0.59
2	0.78
3	1.0
4	1.45
5	1.17

Containerization

The packaging of solidified nuclear waste for disposal in space must be a container which will retain its integrity in all postulated service conditions, must provide a means of dissipating the heat produced by the waste at acceptable temperature levels, and must afford radiation shielding to limit the exposure of personnel involved in the disposal operation. These fundamental requirements must be achieved to make space disposal a viable supplement for waste management. The design of the packaging will be highly dependent upon the waste form and its properties. This study of the packaging design for space disposal of nuclear waste considered the factors of physical and thermal properties of the waste, internal heat generation, shielding requirements, potential criticality limitations, and compatibility of the waste with structural materials. The structural and thermal design of the packaging is influenced by the normal and potential accident conditions occurring during ground transportation and handling, launch, orbital, and postorbital operations.

The tentative design criteria established for the canister are:

(1) Maximum payload per unit weight

(2) Waste density of 4 g/cc

(3) Nominal capacity of 1 cubic meter of HLW

(4) Maximum temperature of 1000 C for HLW (or not to exceed the maximum processing temperature)

(5) Passive cooling after Earth orbit

(6) Ability to survive reentry into the atmosphere, with the cocoon

(7) Ability to survive ocean impact, with the cocoon

(8) All protective packaging is separate from the canister containing the waste

(9) Compatible with a shipping cask which satisfies NRC/DOT requirements and regulations

(10) Compatibility with all phases of the waste stream handling from the processing facility to ejection into space

(11) Minimum number of internal cooling fins to dissipate the decay heat

(12) Total radiation dose (gamma plus neutron) at 1 m from canister surface to be within 2 R/hr.

The initial concept for the waste packaging consists of a thin-walled canister in the shape of a right circular cylinder. The diameter of the canister is approximately equal to its length. Several disc-shaped fins made of a high thermal conductivity material are located normal to the axis of the canister to assist in conducting heat out of the waste. Passages for coolant from an auxiliary cooling system are integral with the canister wall to extract heat from the package. The canister is surrounded by a depleted uranium alloy radiation shield. A heavy stainless steel wall outside of the shield acts as the outer protective shell for the uranium and the structural wall of the reentry-protection cocoon. The uranium is also protected internally by a thin stainless steel shell.

The design basis maximum dose rate is 2 R/hr at 1 meter from the package. This dose rate is higher than for most packaging for radioactive materials but is a compromise to decrease shielding weight while limiting personnel exposure to manageable levels. The package will need to be contained in a shipping cask during transport on public land or waterways to further limit the radiation dose to levels acceptable to NRC/DOT regulations.

A gamma ray and neutron source term for the waste was estimated by calculations with the ORIGEN code and was utilized for assessing the shielding requirements of the packaging. As a design basis the waste was assumed to be from PWR fuel irradiated for 3 years to a burnup of 33,000 MWD/T and processed 0.5 year after discharge; 0.5 percent of the uranium and plutonium remained in the waste. The shield was designed for waste with 10.5 years of decay after reactor discharge. The QAD code was used to analyze the gamma dose and ANISN was used for neutron dose calculations. With 5 MT of high level waste oxide in a cylinder, 117 cm in diameter and length, and assuming the canister and shielding structural walls are 5.5 cm in total thickness, the shielding calculations showed that 5.6 cm of uranium would limit the dose at one meter to approximately 0.5 R/hr from gamma radiation and 2.5 R/hr from neutrons. Whereas this dose rate is 50 percent above the design limit, it is believed that it would be preferable to further reduce the neutron dose by a temporary neutron shield on the external surface of the packaging rather than to incorporate a permanent neutron shield in the packaging.

The thermal design of the package was scoped by performing a series of heat transfer calculations with the TRUMP computer program, a transient and steady-state heat transfer code. The thermal design of the system is primarily based on the bare canister of waste in deep outer space. In this condition the total heat generated in the waste must be conducted to the canister wall from which it is dissipated by radiation. Whereas the low thermal conductivity of the oxide waste would cause excessively high temperatures to occur in the waste in this geometry, the analyses showed that acceptable temperatures can be achieved by adding internal high conductivity fins to promote the transfer of heat to the canister walls. For this design study the fins were assumed to be thin pyrolytic graphite discs the same diameter as the canisters, and spaced at intervals along the axis of the container.

Other thermal conditions for the packaging which were considered included the transient condition during loading of the waste canister until it is placed in the shield assembly, the steady-state condition of the waste canister in the shield assembly, and the shielded canister package in transport and handling modes. These analyses show that auxiliary cooling of the waste canister is necessary to limit the waste temperatures to acceptable levels. This cooling is most effective when applied directly to the canister wall. Absence of cooling during transport and handling must be limited to periods of less than about 4 hours. The most serious thermal condition identified is an accidental fire concurrent with a loss of auxiliary cooling such as would occur during the hypothetical fire defined in the transport regulations.

Scenarios were developed for the various operations from the waste processing facility to postorbital flight for the purpose of identifying problem areas. The waste will be loaded into the canister, the canister cover will be installed and welded, and the assembly inspected in a remote handling cell at the processing facility. During, or shortly after, the loading operation the canister must be cooled. The canister next is inserted into the shield assembly and its cover is installed by remote operations. The shielded package may be transferred to a temporary storage location or may be loaded into a licensed shipping cask and placed on its transport vehicle. The loaded transport vehicle will exceed highway weight limits so transportation will be by rail or waterway. The transporter will have an auxiliary cooling system to provide reliable cooling for the package while in transit. When received at the launch site the shipping cask may be transferred from its railcar, barge, or motor vessel used for transport to a land vehicle for transfer to the launch site receiving facility, each of which will provide cooling for the package. In the receiving facility the package will be unloaded from the shipping cask and the cask returned to the processing facility by its transporter. The shielded waste package will be inspected, and prepared for flight by attachment of the cocoon components to the outer

structural wall of the package. Next the waste package will be transferred to the payload changeout room and loaded into the Shuttle where it will be attached to the onboard cooling system. If a temporary neutron shield is utilized to control the neutron radiation it may be a thin jacket of borated polyethylene which is applied in the receiving facility and removed after the installation of the package is completed in the Shuttle. The cooling system on the Shuttle will remove the waste heat from the launch time until the canister is withdrawn from the cocoon-shield package in preparation for removal from the Shuttle and placement in post-orbital flight.

The study of the transport and handling operations did not reveal any unique problems which would be considered unfeasible by current technology. The most difficult aspect of the total operation is the need to maintain continuous cooling for the waste canister with only brief interruptions throughout its life until it is transported away from the Shuttle in the post-orbital period.

Environmental Assessment

The preliminary environmental assessment reported here provides an initial information base covering both normal activities and unplanned events, political and international implications, and intrusive acts of man. Emphasis has been placed upon the evaluation of hypothetical worst-case events, such that designs and operational procedures are driven to preclude the occurrences of such events. An in-depth "credible" environmental assessment of the preferred disposal concept is not possible until better program definition is achieved. The preliminary analysis presented below, concerning the hypothetical worst-case events, is not intended to be used for a comparison with terrestrial options; however, it is strictly for providing information which will aid in the proper choice of space disposal design and operational alternatives which pose the least risk to man.

A large array of possible environmental issues were identified and given a study priority (see Sections 4.1 and 4.2). Environmental issues that were assigned the highest priority in this study are:

Normal Operations

- Brief review of normal operations
- Political and international implications
- Integrity of space storage/disposal activities.

Abnormal Operations (e.g., accidents or unplanned events)

- Accidents at sea during terrestrial transport to a remote launch site with release of radioactive material
- Space system failures on the pad, during boost, and during LEO operations with release of radioactive material into Earth's biosphere
- Accidents in space
- Intrusive acts of man.

These critical issues are the subject of the environmental analysis described in the body of the report (Sections 4.3 through 4.7). Brief summaries of these findings along with a brief discussion of recommended designs and operational improvements and criteria are provided below.

Environmental Impact from Normal Operations

Three activity areas supporting normal nuclear waste disposal operations in space were defined: (1) post-reactor processing, (2) terrestrial transport, and (3) space transport. Post-reactor processing and terrestrial transport activities would both be the responsibility of the Department of Energy (ERDA). NASA would likely be responsible for providing only the space transportation. A considerable amount of information exists in the literature on the environmental effects of nuclear waste processing and terrestrial transportation (see Sections 4.3.1 and 4.3.2). No significant work has been done to assess the environmental aspects of space transport activities of nuclear waste disposal missions. Therefore, in this report emphasis has been placed upon possible environmental effects of space transport (see Section 4.3.3).

Environmental issues related to normal (planned) space transport activities (see Section 4.3.3) which are addressed in this report are: launch site development, orbit transfer vehicle (OTV) development, Space Shuttle launches, OTV operations, the ultimate disposal of nuclear waste, and Space Shuttle energy requirements.

The preliminary environmental assessment of the normal activities of space transport and the disposal/storage of nuclear waste in space shows that no significant adverse impacts to the quality of the human environment, either in the next two decades or in the long-term future, are expected if mixes other than Mix No. 1 are considered. Mix No. 1 would likely pose significant environmental impacts even if launched from a remote site (~1700 per year by year 2000*). Energy requirements ($\sim 840 \times 10^{12}$ kJ per year) for launch operations alone make serious consideration of disposing of Mix No. 1 unreasonable. Space Shuttle launch rates projected for other mixes (ranging from 2 to 80 per year by the year 2000) do not appear to offer any significant environmental impacts. Impacts would be expected to be similar to those currently predicted for Space Shuttle operations at total launch rates of 60 per year (40 per year at Kennedy Space Center, Florida). The most significant of these are: sonic booms over populated areas, slight ozone depletion, and the possibility for acid rain events (from SRM exhaust). Normal space disposal activities of the various mix options are not expected to have any significant adverse effects either to orbits or to celestial bodies. However, the use of a crater of the Moon as a disposal/storage area would probably preclude the use of that small area for future generations. It is expected that adequate siting studies, which consider all scientific, economic and cultural factors, would be made such that impacts affecting the future use of the Moon would be minimized. Political implications regarding the exclusive use of the Moon are discussed in Section 4.6.

*Note: The NASA/MSFC guideline of two Space Shuttle launches for the disposal of one payload containing 5500 kg of calcined nuclear waste, one for its payload and one for placing the LH_2/LO_2 OTV into orbit, is assumed here.

Worst-Case Abnormal (Accidents/Unplanned) Events

Abnormal events are defined as those events which are postulated to occur as a result of an accident or an intrusive act of man (see Section 4.7). The analysis of worst-case abnormal events (see Section 4.4) may suggest changes in current system design which would ultimately lead to a reduction in the risk to man. In concert with the scope of the present study, only the most critical hypothetical abnormal events associated with the release of radioactive material during space operations were examined.

Worst-case accidents are assumed to result in the release of all of the radioactive waste (~5500 kg) into the lower atmosphere, upper atmosphere, into the oceans or fresh water lakes, and onto the land. All such releases can subsequently affect man and his Earth's ecosystems to various degrees. The abnormal events studied here, which directly affect the Earth and its biosphere, are as follows:

- On- or near-pad catastrophic launch vehicle explosion and fire (major impact to lower atmosphere)
- Launch vehicle explosion and fire at high altitude or reentry and burnup of the nuclear waste payload from orbit (major impact to upper atmosphere—followed by chronic impact to lower atmosphere)
- Water impact resulting from launch vehicle failure or intact reentry of the nuclear waste payload from orbit (major impact to ocean or fresh water)
- Land impact resulting from launch vehicle failure or intact reentry of the nuclear waste payload (major impact to land).

Effects from accidents in space vary according to the space disposal option considered. Accidents in space can result in the release of long-lived radioactive material into various orbits and onto various celestial bodies. Contamination of celestial bodies is not desirable and should be avoided by proper design and operational procedures.

The calculation of the probabilities of the postulated abnormal events as a result of accidents or intrusive acts of man is beyond the scope of this study. The occurrence probabilities of worst-case abnormal events postulated here are believed to be extremely small. Future study efforts will be required to identify credible accident scenarios and accident probabilities.

The baseline assumptions used in the evaluation of the five areas of abnormal events involving the release of all of the nuclear waste payload are as follows:

- Mix No. 3
- Calcine powder waste form
- 5500 kg nuclear waste payload
- Space Shuttle launch vehicle
- Hydrogen/oxygen OTV
- KSC or remote Atlantic Ocean island launch site
- Worst-case scenarios assumed.

Effects on man and ecosystems as a result of postulated worst-case events include: (1) acute toxicity causing death, somatic damage, or reproductive damage; (2) sublethal toxicity which chronically causes disease (cancer), and losses in tissue, organ, organismic, population, or community productivity; (3) bioaccumulation to toxic thresholds; and (4) disruption of vital ecosystem processes, such as nutrient cycling. The degree of these effects depends upon many factors: (1) the type of accident and the environment surrounding the event (demography, type of ecosystems, and physical), (2) the integrity of the container system, (3) the physical characteristic of the waste form, and (4) the waste mix.

For the five types of events considered here, a catastrophic on- or near-pad catastrophic launch vehicle failure at KSC, resulting in the rupture and release of the radioactive waste payload, is considered very serious. A high altitude burnup is considered serious, with other events following in severity [sea, land, and space (lunar) type accidents]. The assessment of effects to man and ecosystems as a result of these events is extremely difficult. However, order of magnitude projections can be made.

In the case of the catastrophic on- or near-pad launch vehicle failure, assuming Mix No. 3, the local human population exposed to the cloud resulting from the fireball containing the radioactive material could receive an inhalation radiation dose exceeding 500 times background (background ~0.1 rem/year). At downwind distances of ~100 km, exposures could exceed 100 times background. Public radiation standards vary from 5 to 15 times background, depending upon the organ or part of the body exposed. If gravitational settling of radioactive particles were a predominant effect, the area downwind of the event would become severely contaminated, many life forms would be destroyed, and the land area would have to be isolated indefinitely.

An upper atmospheric burnup of the payload could result in similar effects, depending upon the particle size distribution of the radioactive material, and the longitude and latitude of the event. Chronic toxicity effects would be expected for the case of worldwide distribution of the material. The amount of strontium-90 which could be released by one accident involving Mix No. 3 amounts to ~40 percent of that released from all nuclear devices through 1962.

For accidents at sea resulting in the release of radioactive material, exposure to man would primarily be by bioaccumulation of nuclides in aquatic food chains. Reduced productivity of aquatic organisms could limit food supplies to man.

Effects caused by a nuclear waste package crashing on land, in a populated area, followed by dispersal of the waste (calcine powder) could be significant. If the waste material is characterized by a fine particle distribution, then the chance for resuspension in the air becomes likely, thus causing severe impacts to local human, plant, and animal populations.

Accidents in space, followed by radioactive releases, are not expected to impact the Earth's biosphere; however, contamination of orbital regions or other celestial bodies (especially the Moon) could preclude the use of an orbit or as a future resource. Strong opposition would be expected from the scientific community, if it were likely to contaminate the Moon or other planets by a waste disposal accident.

Suggested Design and Operational Procedure Criteria and Improvements

Utilizing results of the study and inputs from NASA evaluations, various design and operations criteria and improvements are suggested such that the worst-case events, as defined in Section 4.4, can be avoided or prevented. They are as follows:

Waste

- The waste should be in a solid form such that it is not easily dispersible under the various physical environments possible. This provides for recovery of the material and reduces impacts to large areas and populations.

Container Systems

- During all phases of the disposal mission, if it is possible for the waste payload to reenter the Earth's biosphere, a "cocoon" capable of surviving atmospheric reentry and land and sea impact is recommended. In addition to the reentry cocoon, perhaps a modest container system could be devised such that, after the OTV's guidance system has projected that the vehicle will have a high probability of mission success, the OTV-carried protective shielding could be jettisoned, thus providing the required degree of performance for a reasonably small penalty. This protection shielding would be designed only for reentry survival.
- For a lunar disposal/storage concept it is desirable that the container's passive thermal system be designed such that thermal limits would not be reached if buried in the lunar surface.
- If waste container is lost at sea as a result of shipping or flight accident, the container should survive the high hydrostatic pressure and survive high temperatures that might be experienced if buried in sediment.
- Depending upon which disposal concept is chosen, consideration should be given to container design such that it can survive for many thousands of years.
- The reentry container (cocoon) should be equipped with a radio transmitter and a flotation device.

OTV System

- The chemical OTV's should be designed to have multiple redundancy in critical subsystems, such as to avoid reentry into the Earth's biosphere.
- Consideration of the use of an automatic ejection system for the waste payload during orbit transfer operations on the OTV is suggested.
- Consideration should be given to low-thrust systems (chemical, ion, and sail) for the advantage of providing the capability for a response to OTV failure, and thereby eliminating possible adverse effects caused by the failure if it were to reenter the Earth's biosphere.

Space Shuttle System

- Consideration should be given to improving Space Shuttle reliability for waste disposal missions.

Operations

- Launch constraints should be instituted so that if local dispersion predictions are such that significant human populations could be affected by an accident, the launch would be postponed. This would be done regardless of launch site chosen.
- A remote launch site (island or platform) with minimal land over flight, during the first and subsequent orbits, would minimize the risk to man. Trades between considering first and subsequent orbits as most critical need to be evaluated.
- Adequate safeguards must be assured against intrusive acts of man.
- Provisions should be made for fast response recovery teams, should reentry of the payload occur.
- A lunar waste disposal concept should provide for controlled soft landings at a given site and offer the option for burial operations of the waste (automated or manned).
- Trajectories for the disposal mission should be chosen to minimize the probability of Earth encounter, over a time period such that the waste package becomes relatively less hazardous.

Political and International Implications

With the expansion of national and international activities in space, the nations of the world have seen fit to develop various conventions, treaties, and other multinational instruments to guide the use of space so as not to preclude its use by others and to minimize the use of space as a staging area for possible acts of aggression against other nations. The implications of these various conventions and treaties on the possibility of using the Space Shuttle or another vehicle for space disposal of high level radioactive waste (HLW) present a very real and complex set of issues. In this preliminary evaluation, possible areas of issue or concern were identified from the treaties. The treaties suggest the following issues which must be thoroughly explored in the early decision-making phase:

- Accident liability
  - — on Earth
  - — to other space objects
  - — on space bodies
- Exclusive use
  - — of the Moon surface
  - — of areas of outer space

- International program base
  - source of HLW
  - launch/landing sites
  - processing sites
  - mutual assistance in space
  - use of the sea

- Weapons of mass destruction in orbit.

International cooperation is an important issue in nuclear waste disposal in space. As the use of nuclear power extends to other countries of the world, each of these countries will have nuclear waste which must be managed in some fashion. Before a realistic assessment of the international implications can be made, the degree to which international cooperation is desired in this program must be outlined. Potential interactions include internationally derived nuclear waste, internationally derived processed wastes, international funding, non-U.S. launch facilities, or high seas launch facilities. The International Atomic Energy Association in Geneva, Switzerland, could provide the interface for international aspects when realistic alternative national/international programs have been defined.

Intrusive Acts of Man

Planning against intrusive acts from, and implementing safeguards against, both external and internal threats to the space-based nuclear waste disposal operation is a critical area of overall program planning. One action on the part of a deranged individual or unfriendly group could unravel the framework of operations safety and systems integrity which characterize the nuclear waste disposal effort. Such an act, successfully conducted, could result in severe environmental consequences (local and/or global). In the least case, even if such an act were not successful, it could cause sufficient critical political attention to be focused as to place the entire program in jeopardy. In the report, three aspects of the intrusion problem are discussed: (1) the types of people/groups which are potential threats to the program, (2) the deliberate actions both external and internal to the operation which are possible, and (3) safeguards which could be implemented to prevent intrusive acts.

Summary and Conclusions

The preliminary effort in identifying requirements which are unique to support the nuclear waste disposal in space concept and which might impact the nuclear fuel cycle, as discussed in Sections 1 through 4 of this report, led to the following:

- There are significant uncertainties regarding the Nation's nuclear policy that will affect nuclear waste management.
- It is difficult to define the optimum waste form for space disposal and nuclide mix assuming present technology, but it is likely to be different from that for terrestrial.
- There are no apparent technical reasons why the mixes cannot be prepared.
- The possibility of partitioning Zr and Mo out of the space disposal fraction offers advantages of weight reduction and the prospect of using these materials in useful applications.

- The costs associated with the fuel processing and waste solidification for space disposal are not expected to be significantly different from those for terrestrial isolation.
- The cost of actual emplacement will likely be significantly greater for space disposal of waste than for terrestrial isolation, and may increase the safety of waste management.
- Internal fins for heat transfer will be required in the waste canister if a package with L/D = 1 is used to contain calcine waste.
- Major parts of the container and shielding package can be used for both ground and space transportation, within regulatory standards.
- Suitable state-of-the-art materials exist for the container and shielding.
- Canister designs can be developed which will withstand water impact.
- Nuclear criticality is not a problem with the waste package, except possibly for waste Mix No. 2.
- Normal operations do not impose any significant environmental impact to the Earth's biosphere beyond normal Space Shuttle and OTV operations.
- Use of a crater on the Moon as a disposal/storage site could preclude the use of that limited region of the Moon for other purposes.
- Hypothetical worst-case accidents, should they occur, are extremely serious.
- Disposal of all high level waste (Mix No. 1) in space is impractical because of environmental impact, energy requirements, and economic factors, and warrants no additional study.
- Launch rates required for Mix No. 5 (technetium alone) and perhaps Mix No. 4 (0.1 percent U + Pu, other actinides, and rare earths except Ce) can be reasonably handled at KSC.
- Mixes Nos. 2 and 3 would most likely require a remote off-shore launch site to be developed.
- Of the five accident types treated, the two most severe hypothetical accidents are (1) the on- or near-pad catastrophic failure with subsequent release of radioactive material and (2) the complete burnup on reentry.
- Political and international consideration of space disposal is a complicated and sensitive situation that needs to be dealt with accordingly.

Recommendations

In order for the space option to be viable, it is desirable for NASA and ERDA to jointly evaluate the desirability of pursuing the matter, and to establish an interface activity to define or recommend the fuel cycle and support facilities to incorporate the space option in the overall waste management system including the following:

- Additional feasibility studies are needed to explore available options and resolve unanswered questions. (NASA)*
- Analytical studies followed by experimental efforts on alternate waste forms should be pursued. (ERDA)
- NASA should consider incorporating part of the cocoon into the shielding and canister structure. (NASA)
- In-depth parametric analysis of the canister design and internal heat transfer members should be initiated. (NASA)
- Testing of structural properties for possible materials for canister shielding needs to be undertaken to permit their ultimate licensing and design activities. (ERDA)
- Study of a lunar storage/disposal site should be initiated, including consideration of manned and unmanned disposal operation, controlled soft landings and burial under the surface of the Moon. (NASA)
- Because hypothetical worst-case results are so severe as a result of accidents during space transport, consideration should be given to design of the cocoon-container system to be able to withstand any environment while in the vicinity of the Earth's biosphere. (NASA)
- Launch constraint studies should be initiated. (NASA)
- More in-depth environmental studies should be initiated on the yet-to-be-defined worst credible cases and continued on the hypothetical worst cases. (NASA)
- A fault-tree analysis of the entire space disposal mission should be initiated as part of an overall risk assessment. (NASA)
- Suggested design and operational procedures, as discussed in the text, should be considered. (NASA)
- Discussions between Federal and international agencies should be initiated regarding the legal and political aspects of a space disposal activity. (NASA)
- Further study of intrusive acts and safeguards is required. (NASA)

*Parenthetic notation after each recommendation indicates prime agency responsibility.

1.0 INTRODUCTION

1.1 Reason for Study

The possibility of disposal of nuclear waste in space has been considered before [1-1 through 1-4]* with generally positive judgments on the technical feasibility. The most detailed study[1-3] concluded that the concept was feasible using the Space Shuttle and an expendable tug to insert the waste into a solar system escape mode. Further, it was concluded that separation of the actinides from the balance of the waste, followed by their incorporation into a very complex waste form for subsequent disposal alone was the most cost-effective approach using space disposal technology.

In the meantime ERDA**, although participating in the study of space disposal of nuclear waste, has generally pursued a different high-level waste disposal concept for terrestrial application. This concept involves the mechanical chopping of spent fuel assemblies followed by chemical dissolution of the oxide fuel and contained fission products. The uranium and plutonium in this concept are to be chemically separated and recycled into the reactor to completely utilize their fissile content. The remainder of the material is to be solidified by evaporation and calcining to a mixture of oxides which are then incorporated into an inert glass. The glass is subsequently encapsulated in metal containers which are then isolated in underground repositories located in geologically stable formations for the long periods of time required to allow the radioactivity to decay to acceptable levels.

Recently this concept has been perturbed by an Administration decision to evaluate proliferation-resistant fuel cycles, including a scenario where the spent fuel would be placed directly into long-term storage without chemical processing. This approach was dictated by an increased concern over the possibility of diversion of plutonium from the intended civilian nuclear economy. The reasoning for the new approach goes that, without reprocessing, the plutonium is never in a separated form which could lead to weapons proliferation. Another factor considered in discontinuing reprocessing is the changing public perception[1-5] of the recycle of plutonium. In recent years a vocal segment of the nation's population has insisted that the use of this valuable resource could lead to its uncontrolled dispersion. The same concern exists to a slightly lesser degree for the other components of the waste from reprocessing so that the reasoning followed is that these materials should not be accepted by society for storage on Earth for the extremely lengthy time periods required for decay to safe levels.

Simultaneously, the development of the Space Shuttle by NASA is on schedule and it should be operational by 1980. This technology may present an apparent relatively reliable opportunity to remove objectionable materials from Earth and place them in remote space locations where they can have no effect on mankind or the biosphere. Such an approach, used in conjunction with terrestrial disposal, might offer unique opportunities for improved nuclear waste management.

The intent here has been to identify those major problems or uncertainties of the space-peculiar subsystem of the fuel and waste processing system. Subsequent to this scoping activity, these major items have been addressed in a preliminary manner to permit a judgment as to

*References are listed at the end of each section.
**Acronyms are defined in the Glossary.

whether potential solutions exist that are worthy of further study, and what approaches seem most feasible. This preliminary study covers: (1) post-reactor processing, (2) terrestrial transportation, and (3) environmental impacts as they relate to management of high-level nuclear wastes by disposal in space.

1.2 Generation of Waste in Nuclear Reactors

1.2.1 General Background

The commercial nuclear power industry in the USA currently has an operating capacity of roughly 40 GWe and plans to expand significantly over the foreseeable future. These nuclear power plants discharge their spent fuel on roughly the basis of one-third of the reactor core annually, resulting in an accumulation of highly radioactive material which is very toxic, generates a considerable thermal inventory, and has nuclear half-lives of as much as hundreds of thousands of years. It has been expected that this spent fuel would be reprocessed (i.e., chemically dissolved, followed by recovery of the reusable fissionable materials—uranium and plutonium), although this capability is not a commercial reality today. This assumption of reprocessing and recycle of fissionable materials has recently been deferred indefinitely by U.S. Administration decision. However, there will still be essentially similar amounts of spent nuclear fuel to be safely handled, and the unusable or waste constituents of this fuel present a potential hazard to current and future generations if they are not properly disposed of. Until the decision to defer reprocessing and recycle, inclinations of the U.S. Government (ERDA) were to solidify the liquid wastes from reprocessing into a form which is inert to chemical attack or dissolution, encase it in massive containers and dispose of it in government-controlled repositories on Earth for the eons of time required for its isolation.

Because of the vast body of information relating to this concept, it was decided to evaluate the concept of disposal of the waste in extraterrestrial locations. This would conceivably result in less potential for undesired exposure of the population to this material by its permanent removal from the biosphere. The evaluation is considered to be conceptually valid for any nuclear fuel cycle which will generate waste materials

1.2.2 Baseline Assumptions

The reference nuclear reactor mix upon which this evaluation has been based consists completely of light water reactors (LWR's) to the year 2000, which is the period of study selected to coincide with expected availability of the Space Shuttle as a transport vehicle. The scenario which is assumed for growth of nuclear capacity is that released by ERDA in late 1976[1-6], designated as their Low Case, and reproduced below.

Year	GWe
1975	39
1980	60
1985	127
1990	195
2000	380

Such predictions are noteworthy for the short duration of their validity, not from any lack of ability or effort but due to the rapidly changing environment in which they are made. However, plans and decisions must be made to form a basis for action, and assumptions upon which the plans are made must be derived from the best possible estimates of capacity.

The LMFBR was eliminated from consideration, first based on the research team's assessment of unlikely commercialization in time to have solidified wastes available for disposal prior to 2000; i.e., with the 10-year elapsed time between reactor withdrawal and waste disposal. Subsequently, this decision was reinforced by the nuclear policy announced on April 7.

The LWR's were considered to be operable in the "throwaway" mode without U or Pu recycle and to be operated to a uniform fuel burnup of 33,000 MWD/T. This latter assumption is recognized as being slightly above general practice, but thereby results in conservative design of system components. However, it is assumed that reprocessing facilities are available where it might be desirable to go through the head end (chop and dissolve fuel from elements) of reprocessing to generate a waste stream consisting of the entire fuel assembly, less hulls. Such an activity was conceived as a method of substantially reducing the waste volume as compared with disposal of complete fuel assemblies. The LWR waste situation was also examined from the standpoint that either uranium or plutonium, or both, might be separated from the waste stream and ultimately recycled. The latter was to establish a direct comparison with the historic reference waste management philosophy. Finally it was considered that there should be the capability to partition (i.e., selectively remove) some nuclides from the liquid waste and thus achieve the flexibility of choosing specific isotopes for space disposal while leaving less hazardous materials on earth where they might be safely stored in engineered facilities.

1.3 Nuclear Waste Handling

1.3.1 Nuclear Fuel Cycle

The nuclear fuel cycle including the commercial nuclear reactor plants can be discussed generically from the standpoint of waste produced, regardless of the fissile material (U-235, Pu-239, or U-233) involved. However, this study was directed toward the U-Pu fuel cycle which had been considered as the reference system for commercial light water reactors (LWR's) for a number of years.[1-7,1-8] It should be recognized that midway through the study this reference fuel cycle was declared to be indefinitely delayed by a revision in national policy[1-9], and a throwaway cycle instituted.

Each step in any nuclear fuel cycle starting with the mining of the ore and culminating in final storage of the wastes has some potential for the release of radioactivity, either through operational failure or some design or processs inadequacy. The regulations that protect against such inadvertent releases are evolving constantly to protect the environment. It is not the purpose of this study to discuss the U-Pu fuel cycle in detail: suffice it to say that the fuel reprocessing stage is the fuel cycle step involving the greatest chance for significant release of radioactivity. Nevertheless, the evaluation of the U-Pu cycle was undertaken to permit an assessment of the relative merits of space disposal of high-level wastes compared to terrestrial disposal. This decision was based upon several factors.

- Even with a throwaway fuel cycle, it is conceivable that an abbreviated reprocessing operation might be desirable for volume reduction of high-level waste from that associated with complete fuel bundles.

- The ultimate decision on nuclear power may be made in favor of the U-Pu fuel cycle, especially if uranium resources are limited.
- Alternate fuel cycles based on U-Th will require reprocessing with generation of wastes that are similar to that associated with the U-Pu cycle.
- Alternate reprocessing methods, e.g., coprocessing and pyrometallurgical techniques, will generate large volumes of high-level wastes for disposal.

The industrial maturity of fuel mining, milling, conversion, enrichment, fabrication and reactor plant stages of the fuel cycle is not matched by that of the fuel reprocessing and high-level waste storage steps. The basic technology for reprocessing, the Purex process, was developed over 25 years ago and has been improved continually in that time. No significant commercial industry was developed due to the small volume of business as compared to the inherent economic desirability of operating the Purex process continuously, so that a backlog of spent fuel was allowed to accumulate. One small commercial plant (~300 MT/yr capacity) was operated by Nuclear Fuel Services for approximately 6 years at a low capacity factor, but has since closed due to changes in regulatory requirements. A second plant, of 300 tons-per-year capacity, was mothballed by General Electric in 1974 after completion of construction, and was never operable because of technical difficulties. A third plant of 1500-ton capacity being built by Allied Gulf Nuclear Services (AGNS) is nearly completed but startup is delayed pending clarification of government policy. Finally, design has been completed by Exxon and site acquisition undertaken for a 2100 ton-per-year plant.

1.3.2 Character of High-Level Waste

The high-level nuclear wastes derived from reprocessing of spent reactor fuel assemblies are produced when the assemblies are mechanically chopped and the fuel pellets are then dissolved in 2 to 3 M nitric acid. U and Pu are then coextracted from the aqueous solution into an organic phase of tributyl phosphate dissolved in kerosene. The two actinides are subsequently separated by selective oxidation and solvent extraction and in the fuel recycle mode of reactor operation are then sent back into the fuel fabrication plants.

The aqueous raffinate from the above process is generally considered the high-level waste. The major constituents are the fission products; the actinides which include all of the Np, Am, and Cm and small amounts of U and Pu; and nitric acid. In addition, there are lesser amounts of corrosion products and deliberate inert additives used for control of chemical reactivity. In these categories are Gd, Fe, Cr, Ni, Na, etc. The precise composition of this waste depends on a number of variables.[1-10] The nuclides present are a function of the reactor type, the original fuel composition, burnup achieved, the time elapsed from reactor discharge, and other factors such as slight changes in reprocessing chemistry.

While not normally considered as high-level wastes, there are gaseous isotopes of C, I, Kr, etc., which are released during reprocessing. It may be desirable or required to capture and immobilize these materials to minimize human exposure.

1.3.3 Need for Isolation of the Waste

The stage of the nuclear fuel cycle presenting the greatest long-term concern is that of storage or disposal of the high-level waste since eons of time are involved with attendant technological, social, and institutional problems. The biological significance of the waste materials during this period derives from a number of factors, including the intense penetrating radiation, toxicology, and high specific heat content. The half lives of the isotopes, which predict the time of decay of the radioactive and heat emissions, vary from essentially zero to millions of years. It requires 10 half-lives for the isotope to decay to 0.1 percent of its original level, a generally acceptable degree of activity.

Different organs of the body and different forms of living matter are affected differently by radioactivity. The effects to mankind of radiation exposure may vary from temporary illness, through cancer or genetic change, to death.

1.3.4 Separation of Waste Constituents

The subject of partitioning to selectively remove components from the high-level waste mixture will be addressed in later sections. It appears that it is technically feasible to accomplish a number of such partitions, but the economics and environmental impact of such processes are not quantified. This selective removal can be used to extract useful elements other than uranium and plutonium or to segregate the most harmful nuclides requiring rigidly controlled isolation from those which are less demanding in terms of their control.

While the high-level waste is normally considered to be an undesirable material, there are components of that mixture which do have potentially valuable attributes.[1-11] As examples, there are isotopes with unique advantages as special purpose energy sources such as Sr^{90} which can be utilized in static or dynamic conversion devices to generate long-term electrical energy in remote locations. Another example is the use of cesium for the treatment of sewage to eliminate bacteria. A third example is the platinum metal family, for which the U.S. is now completely dependent upon foreign imports, and which is becoming increasingly in demand for catalytic and corrosion-resistant applications. Effective methods of recovery of these materials from the high-level waste might be combined with other partitioning processes to serve a beneficial national purpose. In addition to the attractive uses for such isotopes, the removal of Sr and Cs would aid long-term storage of the other wastes. While partitioning seems to be technically feasible, the practical achievement may be considered only as a future possibility. At a recent conference[1-12] on partitioning, a preliminary assessment of partitioning indicated that this technology should not be a significant factor in waste management strategies in the near future.

1.3.5 History of Disposal of Waste

The subject of safe disposal or controlled storage of high-level nuclear wastes has been recognized as being important throughout the history of the nuclear industry from the advent of the Manhattan Project which developed the first atomic weapon. Wastes have been accumulated and maintained in temporary storage of various types in a generally accepted manner without major exposure of the biota to significant amounts. For high-level liquid wastes generated in fuel reprocessing, the practice has been, since the earliest days of the Manhattan Project, to store them underground in large tanks. It was anticipated that the tanks

would last 20 to 30 years, during which time some permanent method for disposal would have been devised. In any event, solutions could be pumped from old to new tanks in case a permanent waste form and method for disposal had not yet been developed. It is now more than 30 years since the first waste storage tanks were utilized and the ultimate form and method for disposal are still not fixed.

Current regulations and practices relegate to the government the responsibility for ultimate waste disposal. The commercial reprocessor has the responsibility for interim storage of the wastes for a maximum period of 10 years. Furthermore, he can store the waste as liquid for only 5 years, after which he must convert it to a solid form for shipment to the designated government repository.

ERDA is in the process of developing a Generic Environmental Impact Statement (GEIS) to formally evaluate the environmental impacts of various technologies in the management of commercial nuclear waste. While not yet released, the document has been described[1-13] in some detail and it will cover the activities of storage, treatment, transportation, and final disposition of radioactive wastes generated after removal of spent fuel from a reactor. The GEIS has not been published, nor is the definition of the reprocessing required for space disposal, so that sufficient information is not available to permit an evaluation of the differences in environmental impact that might be engendered by ultimate disposal of waste in space.

1.3.6 Methods of Waste Disposal (Current)

Studies to develop ultimate waste forms and systems for waste disposal have been carried out continuously, at a rather low level of effort, since the wastes were first generated. In the early 1960's these efforts were accelerated, particularly with respect to methods for conversion of the stored waste solutions to solids. Such studies were expanded later in the 60's to include conversion of current wastes to solids and conversion of these solids to an ultimate form for disposal. In recent years, an order of magnitude step-up in program efforts has occurred as the growth rate in nuclear power has accelerated and the need has become more urgent. The current program is aimed at resolving the nature of the ultimate waste form and the system for its disposal.

Generally high-level liquid waste volume is reduced by evaporation and the material is then solidified. The most well-developed process involves a continuous spray calciner, followed by vitrification into a borosilicate glass which is then loaded into a sealed metal canister. Type 304L stainless steel is currently being used for the canister.

Gaseous radioactive products can be immobilized to insure their safe storage. For example, iodine can be converted to the pentoxide; tritium as tritiated water can be absorbed into various media; krypton can be absorbed on zeolite; and C-14 can be oxidized to CO_2, reacted with calcium hydroxide to form calcium carbonate, and then mixed into cement.

The reference ultimate disposal mode for high-level waste has been deep geological burial using conventional mining techniques in formations having good ion exchange potential, low permeability, no ground water, a stable history, and freedom from seismic activity. Total costs for ultimate storage after receipt at the disposal site are estimated to be in the range of $10 to $30/kg of heavy metal.

Transportation such as is required to move solidified high-level waste from a reprocessing plant to a site for ultimate disposal is a consideration of this study also. Materials for civilian nuclear use have utilized common carrier-type systems such as rail or truck.

With time, the packaging specifications have become increasingly more sophisticated with the aim of insuring containment of the radioactive material under the worst conceivable accident conditions. In particular, with respect to spent fuel shipping casks, even in an accident that demolished the vehicle, the cask is likely to retain its integrity. The casks for spent fuel transportation weigh many tons and are required to withstand the impact of a 30-ft free-fall followed by a 30-min exposure to a 1073 K temperature associated with a petroleum fire. Casks for solidified waste will be similar although the requirements for nuclear shielding and heat dissipation will probably be somewhat less.

Casks intended for shipment by truck have been common in the past, but a recent reluctance of regulatory agencies to grant load limit variance permits has now made rail shipments more practical. Barge shipments may have advantages where appropriate routes exist, but no casks have been specifically designed for this mode of transportation.

1.4 Waste Availability

There is currently a lack of resolution of the availability of solidified high-level waste for ultimate disposal in any manner. Federal regulations now require that the solidified waste will be transferred to an ERDA-controlled repository 10 years after reprocessing, and for the waste to have been solidified for 5 years prior to the time of transfer. With this criteria, a review of the actual current reprocessing and waste handling capability in the country is in order. There is currently no solidified waste in an acceptable form for disposal, nor for that matter is there a fully qualified and accepted waste form.

The actual inventory of spent fuel now on hand from the 64 operating commercial nuclear reactors is relatively modest, i.e., about 2500 MT (a term denoting metric tonnes, or 1000 kg). Projections of commercial nuclear waste generated by the year 2000 approximate 100,000 MT.

On the other hand, high-level waste generated by the U.S. military program for weapons production approximate 75 million gallons, a quantity which will continue to grow with time. The military wastes are not included in the discussions that follow, nor are wastes that are generated by reactors in foreign countries, even though there might be desirable aspects of an international venture in this area.

If it were assumed that there were a waste form defined in late 1977 (which is considered impossible), if the almost completed AGNS reprocessing plant were fully operational and licensed at the same time (again a very unlikely event), and if the necessary waste handling and solidification facility could be designed, constructed, and made operable in the 5-year grace period allowed from the start of reprocessing (which is possible, but unlikely), then there could be high-level waste available in 1987. This situation, unless unforeseen events arise to accelerate the schedule, must be considered to have slipped by at least 2 years, and probably more, due to the government decision to reevaluate the nuclear fuel cycle. Thus, reprocessing will not likely begin before 1980. There are other intangible factors that relate to a possible corporate decision by AGNS to discontinue plans to remain in this business, but assuming the decision is positive, it is possible that waste could be ready for disposal by 1989 or 1990. This would be generated at the rate of roughly 50 reactor discharges per year which is the AGNS full capacity.

At some time in the future a second reprocessing plant would come into existence to shoulder the additional spent fuel load available. This second plant would be assumed to be built and operated by Exxon, and would have a capacity of handling ~70 reactors full time. However, if Exxon were to start construction in 1978 (an unlikely situation in view of the current atmosphere) their plant would in all probability not be fully operational before 1985 so that additional waste for disposal would be available in approximately 1995. All of these comments apply to waste from freshly discharged spent fuel. If 10-year-old spent fuel is processed, additional waste will be available in 1986. No other plans for commercial plants have been announced at this time.

All of these dates would of necessity slip by as much as 5 to 10 years if significant departure from state-of-the-art reprocessing technology were required to achieve partitioning or if a waste form of significantly different characteristics from that needed for terrestrial disposal were required for space disposal.

The final uncertainty in timing is associated with the regulatory process associated with the nuclear industry. Based upon increasingly stringent requirements which are constantly added to nuclear plants of all types, it is expected that delays of 2 or 3 additional years might be encountered, unless a national commitment to nuclear power were made.

Another consideration relating to availability is that of location where the waste will be available. At this juncture, it must be assumed that the solidified waste form will be centrally prepared at the commercial reprocessing plants, so that it is probable to expect only two locations (AGNS and Exxon) to be producing significant waste for disposal prior to the year 2000. Both of these are located in the Southeastern U.S. (at Barnwell, S.C., and Oak Ridge, Tenn.) in fairly close proximity to NASA's Kennedy Space Center so that transportation to the launch site is relatively straightforward. In addition extensive duplication of handling facilities will not be required.

A total consideration of high level waste according to the plutonium utilization scenario would also include waste generated by the reprocessing of recycle fuel. It is currently considered that such material will not be available in any significant quantity prior to 2000. The reasoning for this is derived from logical timing which follows a progression from AGNS being operable in 1978. The plutonium would be refabricated in about 2 additional years, irradiated in a reactor for approximately 3 years and cooled for 6 months, thus being available for reprocessing no earlier than 1984. With the anticipated backlog at reprocessing plants, 2 additional years of waiting is assumed so that release from the reprocessing plant would be in about 1986. With the 10-year period of time prior to delivery of the waste to an ERDA repository, 1966 is the earliest foreseeable date for space disposal. The optimism associated with this timetable is such as to mitigate against its actual achievement. Since the waste from recycle fuel has slightly different characteristics from a once-through cycle, the effort to evaluate its impact on space disposal could not be justified in this program. In any case the characteristics of the total mix will be little altered.

1.5 Description of Space Disposal Concept

The reference concept for extraterrestrial disposal of high-level waste has been generated through choice from a considerable number of variations for each step along the way from reactor to ultimate disposal. A schematic representation is shown in Figure 1-1 showing the options considered and the reference choices made (in blocks). Briefly, it was decided that

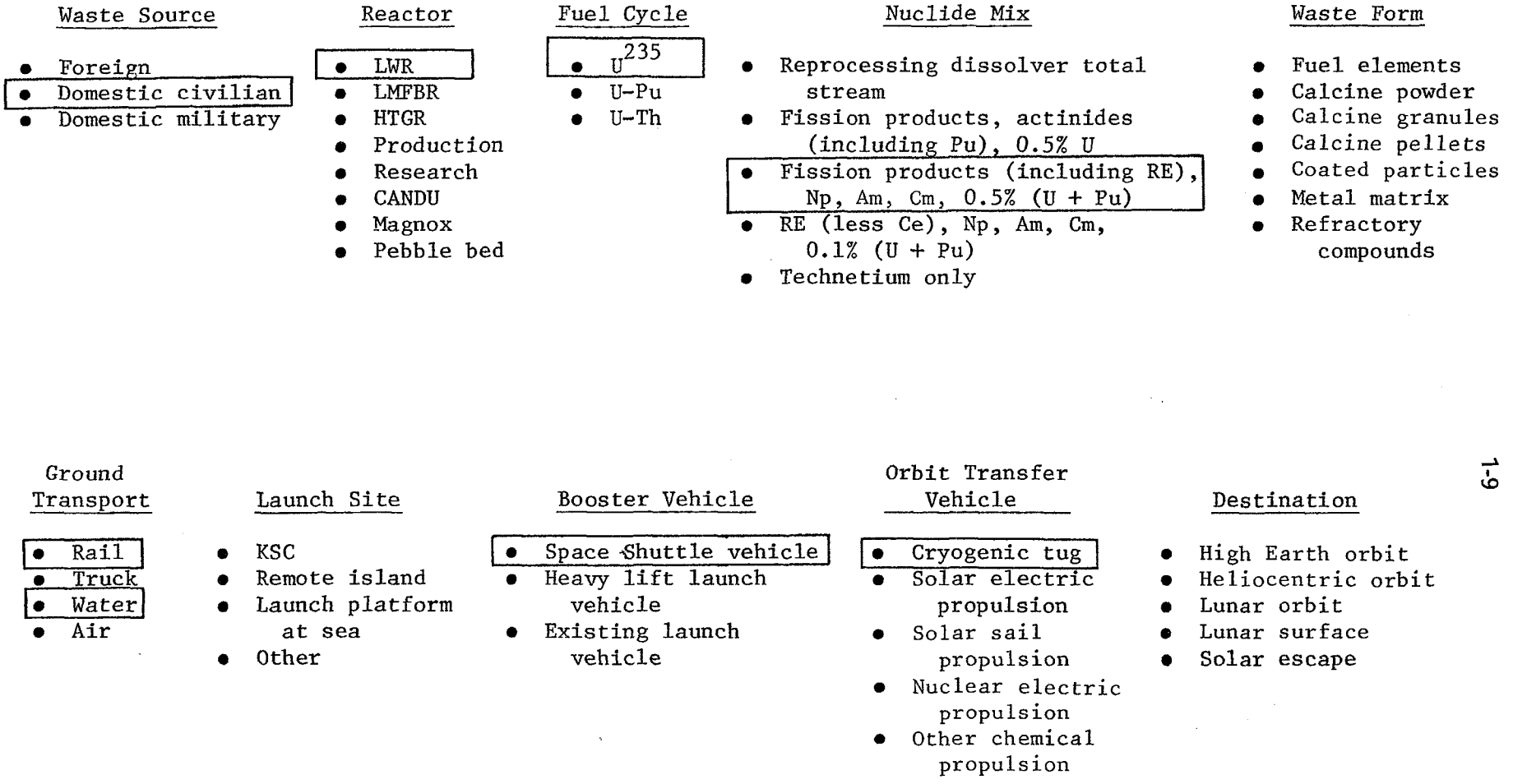

FIGURE 1-1. SCHEMATIC REPRESENTATION OF DISPOSAL OPTION STEPS

only spent fuel from domestic light water reactors (LWR) will be considered, and that the reactors would operate only in the once-through U^{235} mode, although the U^{235} and Pu fissile material would be separated and stored for possible future use by reprocessing. The post-reactor processing method would be essentially that developed for U and Pu recycle through the dissolution step. Various methods of separating the waste stream from this chemical plant into different mixes were considered, almost all of which would demand technology modifications. The reference mix for disposal was chosen by comparing its characteristics against pre-chosen criteria, as follow:

- Minimum perturbation of post-reactor processing
- Minimum weight and volume
- Maximum benefit to man of disposal
- Minimum proliferation potential.

The physical form of the waste was found to be most critical in terms of ultimate space handling. The reference form chosen was pelletized calcine material since it is the best currently developed form when measured against the criteria above; however, to realize the maximum benefits of space disposal it is obvious that some other waste form will need to be developed, with higher density and better thermal conductivity. The waste form is loaded into the canister to be used as its permanent container, shipped by appropriate carrier to a launch site, loaded into the cocoon, which is the safety shield for protection during transportation to space, after which it is removed, placed in the cargo bay of the Space Shuttle Orbiter and launched to a parking orbit. Prior to the launch of the payload, a Space Shuttle vehicle will place in orbit an Orbit Transfer Vehicle (OTV) fully loaded and checked out. Upon arrival and rendevous in the parking orbit of the Space Shuttle Orbiter carrying the payload, the cargo bay doors will be opened and the three-axis controlled cocoon carrying the nuclear waste package will be deployed. The hatch on the cocoon will open, such that the docking mechanism of the OTV can attach to the waste canister inside. The OTV will then actively dock to the waste canister and remove it from the cocoon. The cocoon will then remain passive and be recaptured by the Space Shuttle Orbiter, while the OTV will slowly move out of the vicinity (using 3-axis RCS) prior to OTVs first propulsive maneuver starting the waste to its space destination.

Several propulsion technologies exist which could be utilized as an OTV. Options that have been identified in the past are cryogenics (H_2/O_2), other chemical systems (MMH/NTO, H_2/F_2, N_2H_4/F_2, and solid), solar electric propulsion (SEP), nuclear electric propulsion (NEP), and solar sail propulsion (SSP). Each system has its advantages and disadvantages. Currently, NASA/MSFC believes that the H_2/O_2 OTV is the most desirable.

Various space destinations for waste disposal have been considered. These are high Earth orbit, lunar orbit, lunar surface, heliocentric orbits, and solar system escape. Propulsion requirements, the type of OTV available, economics, desire for storage, and the risk to man which could result from possible accidents will ultimately dictate which destination is favored.

1.6 Space Disposal Advantages

It was a major intent of this study to evolve space mission scenarios and their enhancement of terrestrial waste disposal options to determine if there were real and significant advantages which make it especially attractive in conjunction with Earth disposal. To do so on a quantitative basis is impossible since there is no actual operating experience even for terrestrial high-level waste disposal, so that capital cost and operating expenses are subject to

conjecture. Some rather detailed studies have been made[1-4,15], but actual data are unavailable. Thus the study must be qualitative in nature, and must also be kept in proper perspective.

The briefest of examinations of the two processes shows that much of the existing technology for terrestrial disposal can be used for space disposal, although modifications will be required in many cases. The most obvious conclusion reached after the cursory thinking is that the volume and mass of total expected spent nuclear fuel assemblies, in the next 20 years or so, will exceed the capacity of any reasonable number of launches of the Space Shuttle or even heavy lift launch vehicles. Therefore ways must be developed to minimize the mass and volume, or to selectively remove the most undesirable of the waste components from the bulk mixture and eject them from the earth. In addition, physical and chemical properties of the waste form for space disposal will almost of certainty be different from those required on Earth.

1.7 Uncertainty in Reprocessing and Waste Policy

Recently, the Carter Administration has announced a revision of nuclear energy policy that may have dramatic impact upon the waste management program in the U.S. There are several aspects of the policy, all of which are directed toward the intent of decreasing the possibility of proliferation of nuclear weapons throughout the world. The most important considerations with respect to the study of disposal of high-level wastes are as follow:

- The U.S. will defer indefinitely the reprocessing and recycle of plutonium produced in its civilian nuclear power program.
- The U.S. will redirect funding of research and development to accelerate an evaluation of alternate fuel cycles which minimize proliferation probability.
- The U.S. breeder program will be given greater priority to alternative designs and fuel cycles, and the commercialization of breeders will be delayed.

There are a number of implications that may be drawn from these considerations; however, it may be premature to reach firm conclusions. First, it is conceivable that after the evaluation processes are completed the decision may be reached to proceed with the implementation of plutonium recycle with appropriate conditions of safeguarding, etc., with the attendant generation of large quantities of waste for disposal. Second, the use of alternate fuel cycles involving a wide variety of combinations or uranium, plutonium, other actinides and various fission products which are being considered will of necessity require chemical reprocessing, followed by reuse of the unused fissile content to obtain maximum fuel utilization, especially if some version of a breeder is introduced into the economy. Because of the nature of the fission process, the difference between the high-level wastes from the various cycles is mostly a matter of relatively minor variations in composition. For example, even the nominal uranium-thorium denatured cycle will have in the reprocessing stream significant quantities of plutonium derived from neutron capture by the U-238 denaturant. This cycle also demands a reprocessing step since the U-233 fissile isotope on which the cycle is dependent is nonexistent in nature and must be chemically extracted from a thorium precursor after reactor irradiation. It is also likely that any other fuel cycle developed will have a residue of high-level waste to be disposed of. Thus, it is probable that there will be significant quantities of high-level waste to be properly handled in any future nuclear scenario.

In addition, it should be remembered that there is a large quantity of high-level waste that has been accumulated from the nation's military nuclear program. While not a subject of this study, such material should be considered as a candidate for extraterrestrial disposal, especially when the time frame is extended to the year 2000.

Section 1 References

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2.0 POST-REACTOR PROCESSING

Post-reactor processing involves taking the spent fuel after it is discharged from nuclear power reactors, and processing it into a form that will be easily handled and present less of a hazard to man. This section explores post-reactor processing as it relates to the possible disposal of high-level waste (HLW) in space. Section 2.1 presents information on nuclear waste projections. Possible terrestrial waste disposal alternatives and their cost are discussed in Section 2.2. The various waste mixes considered for space disposal are discussed in Section 2.3. Section 2.4 explores partitioning and develops the preliminary flowsheets for the five possible partitioning options. These options range from sending into space all the spent fuel except fission gases and fuel structural materials, to sending only the technetium present in the spent fuel into space. Section 2.5 looks at the various solid forms the waste could be put into for space disposal. The options include those currently being explored for terrestrial disposal and possible future forms. A general property comparison of oxides, borides, carbides, and nitrides is made in this section since these other compounds could possibly become viable alternatives for space disposal.

The comparisons and estimates made in this section are preliminary. The option flowsheets given in Section 2.4 are only a few of many possible partitioning methods. The possibility of the options working up to the levels of efficiency assumed can only be shown after the options have been experimentally evaluated. The possible use of alternate waste compounds needs to be explored in depth to determine their merit as possible useful forms. Much work needs to be done in the realm of post-reactor processings before it will be a useful companion to space disposal of waste.

2.1 Waste Nuclide Projections

The amount of waste produced and processed needs to be determined to allow the projection of the Space Shuttle traffic since the frequency of the launches will be determined by the amount of waste ready for disposal. This section will explore the future production of spent fuel and the future processing of that fuel. An estimate of the amount of waste eligible for space disposal will be made using information developed in Sections 2.3 and 2.4.

During the normal operations of a nuclear power plant, spent fuel is produced. This spent fuel contains both waste nuclides and nuclides (uranium and plutonium) that can be recycled back to a nuclear power plant. The amount of spent fuel produced depends on the nuclear capacity of the United States. The nuclear industry capacity has recently been estimated for low, medium and high growth cases for the years 1975 to 2000.[2-1] This report will concern itself with the low growth case. Table 2-1 shows the estimated nuclear capacity assessing a low growth rate which is currently the most realistic growth rate. Oak Ridge National Laboratory (ORNL) has published a report on waste projections using the values for the middle case,[2-2] which now seems excessively high.

The processing of the spent fuel requires complex processing plants. The processing capacity required for the U.S. nuclear industry can be estimated for the "low" case. As of 1975, ORNL estimated that there was a backlog of 1365 MT of spent fuel requiring processing. Table 2-2 shows the annual spent fuel, processing backlog, and processing capability for the years 1975 to 2000. It can be seen that the projected processing capacity does not catch up or keep up with the production of spent fuel, causing a continual growth in the backlog.

TABLE 2-1. ESTIMATED NUCLEAR OPERATING CAPACITY, GW(e)[5]

Year[1]	LWR[2]	HTGR[3]	Total
1970	5.0	0.0	5.0
1971	8.0	0.0	8.0
1972	10.0	0.0	10.0
1973	15.0	0.0	15.0
1974	23.0	0.0	23.0
1975	39.0	0.0	32.1
1976	43.2	0.0	43.2
1977	47.8	0.3[4]	48.1
1978	51.9	0.3	52.2
1979	56.3	0.3	56.6
1980	60.1	0.3	60.4
1981	70.1	0.3	70.4
1982	81.6	0.3	81.9
1983	92.8	0.3	93.1
1984	109.4	0.3	109.7
1985	126.8	0.3	127.1
1986	140.8	0.3	141.1
1987	153.7	0.3	154.0
1988	166.3	0.3	166.6
1989	179.8	0.3	180.1
1990	194.8	0.3	195.1
1991	210.7	0.3	211.0
1992	227.5	0.3	227.8
1993	244.3	0.3	244.6
1994	263.2	0.3	263.5
1995	283.0	0.3	283.3
1996	302.8	0.3	303.1
1997	322.6	0.3	322.9
1998	342.4	0.3	342.7
1999	362.2	0.3	362.5
2000	380.2	0.3	380.5

(1) Data given for year end.
(2) LWR = light water reactor.
(3) HTGR = high temperature gas cooled reactor.
(4) Fort Saint Vrain Demonstration Plant.
(5) GWe = Gigawatt electric.

TABLE 2-2. PROCESSING INFORMATION, MT(1) HEAVY METAL

Year	Annual Spent Fuel	Annual Processing Capability	Projected Processing Backlog
1975	459	0	1,365
1976	663	0	2,028
1977	889	0	2,917
1978	1063	0	3,980
1979	1175	0	5,155
1980	1282	0	6,437
1981	1379	500	7,316
1982	1544	1000	7,860
1983	1799	1500	8,159
1984	2061	1500	8,720
1985	2376	1500	9,596
1986	2768	2200	10,164
1987	3144	2800	10,508
1988	3463	3500	10,471
1989	3759	3500	10,730
1990	4062	3500	11,292
1991	4384	3500	12,176
1992	4726	3500	13,402
1993	5083	3500	14,985
1994	5449	4200	16,234
1995	5838	4800	17,272
1996	6259	5500	18,031
1997	6687	5500	19,218
1998	7109	5500	20,827
1999	7525	6200	22,152
2000	7932	6800	23,284

(1) MT = metric tonnes.

The disposal of waste in space requires the waste to have been out of the reactor at least 10 years to allow sufficient time for the radiation and heat generation levels to decay to a level more easily handled. Two alternatives for making waste available for space disposal have been developed. Alternative 1 calls for a time span of 5 years between the processing and solidification of the waste and then allows 5 years between solidification and launch time. This alternative does not account for the age of the spent fuel, rather it assumes that all waste is removed from the reactors 6 months prior to processing. Alternative 2 attempts to account for a cooling period longer than 6 months prior to processing. This will result from the current large backlog of spent fuel in storage which will be the first waste to be available for space disposal. Table 2-3 shows the cumulative amount of spent fuel having been processed and the annual amount of waste eligible for space disposal for the two alternatives.

The estimated amount of waste for space disposal is a function of both waste form and partitioning option; the various waste forms are discussed in Section 2.5, while the partitioning options are discussed in Section 2.4. To quickly estimate the total amount of waste that will require space disposal, a matrix was developed showing the approximate multiplication factor for each waste form and partitioning options. The matrix, shown in Table 2-4, was developed from information in Sections 2.4 and 2.5 for the following five waste mix options:

(1) The fuel is leached and the entire dissolver solution is solidified and shipped into space.

(2) 99.5% of the uranium is recovered from the dissolver solution. The remaining dissolver solution is solidified and sent into space.

(3) 99.5% of the uranium and plutonium is recovered from the dissolver solution. The remaining dissolver solution is solidified and sent into space.

(4) 0.1 of the uranium and plutonium, the balance of the actinides and all the rare earths except cerium are solidified and sent into space.

(5) 99.5% of the uranium and plutonium and 94%* of the technetium are recovered from the dissolver solution. Only the technetium is sent into space.

The mass of waste disposed of in space also depends on the amounts of inert material added to the process streams. It is assumed that 7.2 kg of inert materials/MT heavy metal are found in the waste streams for Options 2 and 3. There are essentially no inerts for Option 1. There will be about 1.5 kg inert material/MT heavy metal processed for Option 4, while Option 5 assumes that the waste contains less than 0.5 kg/MT of inerts. The actual values may be less than this, but can only be determined experimentally. It was determined in Section 2.5 that the oxide forms contain 85% waste, the borides contain 74% waste, the carbides contain 89% waste, and the nitrides contain 90% waste. These values are averaged over all nuclides, but for the various option products, the percentages will change. The average values were used in developing Table 2-4, and it was assumed that no volatile nuclides were lost during solidification. Although this is not entirely true, it is an adequate assumption for making a rough estimate. Table 2-4 also assumed that no gaseous or liquid fission products were present in the dissolver solution.

*94% is current state of the art to be effective; 99% removal will be required.

TABLE 2-3. SPACE DISPOSAL WASTE AMOUNT, MT HEAVY METAL

	Alternative I			Alternative II		
Year	Cumulative Amount Processed	Available for Annual Disposal	Cumulative Disposal	Cumulative Amount Processed	Available for Annual Disposal	Cumulative Disposal
1975	0	0	--	0	0	--
1976	0	0	--	0	0	--
1977	0	0	--	0	0	--
1978	0	0	--	0	0	--
1979	0	0	--	0	0	--
1980	0	0	--	0	0	--
1981	500	0	--	500	0	--
1982	1,500	0	--	1,500	0	--
1983	3,000	0	--	3,000	0	--
1984	4,500	0	--	4,500	0	--
1985	6,000	0	--	4,635	1365	1,365
1986	8,200	0	--	6,172	663	2,028
1987	11,000	0	--	8,083	889	2,917
1988	14,500	0	--	10,520	1063	3,980
1989	18,000	0	--	12,845	1175	5,155
1990	21,500	0	--	15,063	1282	6,437
1991	24,500	500	500	17,184	1379	7,816
1992	27,000	1000	1,500	19,140	1544	9,360
1993	29,000	1500	3,000	20,841	1799	11,159
1994	31,700	1500	4,500	22,980	2061	13,220
1995	35,000	1500	6,000	25,404	2376	15,596
1996	38,300	2200	8,200	28,136	2768	18,364
1997	41,000	2800	11,000	30,492	3144	21,508
1998	43,000	3500	14,500	32,529	3463	24,971
1999	45,700	3500	18,000	34,970	3759	28,730
2000	49,000	3500	21,500	37,708	4062	32,792

TABLE 2-4. PRELIMINARY SPACE DISPOSAL MULTIPLICATION VALUES

Solid Waste Form	Waste Mix Option				
	1	2	3	4	5
Oxide (calcine)	1.17	0.060	0.049	0.0127	0.0015
Borides	1.34	0.068	0.056	0.0145	0.0017
Carbides	1.11	0.057	0.047	0.0120	0.0014
Nitrides	1.10	0.056	0.046	0.0119	0.0014
Supercalcine	1.68	0.086	0.071	0.0182	0.0022
Coated Pellets	1.81	0.092	0.076	0.0196	0.0023
Metal Matrix	1.81	0.092	0.076	0.0196	0.0023
Glass Borosilicate	3.52	0.181	0.148	0.0381	0.0045

The purpose of Table 2-4 is to estimate the amount of solidified waste that is present for disposal for a certain reprocessing alternative, year, partitioning option, and solid waste form. The estimation will give a value in terms of MT of solid waste. For example, take Alternative 2 in the year 1988 as given in Table 2-3; the value found is 1063 MT of waste ready for disposal. If we assume that partitioning Option 3 is used and the waste is solidified in the form of a supercalcine, we get a multiplication factor of 0.071 from Table 2-4. Multiplying these values together we get a value of about 75 MT. This is the amount of solidified waste requiring space disposal for the sample case. The amount of waste to be disposed in space for any other possible disposal system can be closely estimated in the same manner as outlined above, but the exact value can only be obtained after a detailed study.

2.2 Terrestrial Waste Management Systems

The high-level nuclear waste from the processing of spent fuel requires isolation from the biosphere to eliminate the risk to man. The possible isolation methods include geologic disposal, transmutation, or space disposal. This section will summarize only the terrestrial methods: geologic disposal (which is interpreted as including the oceans and ice caps) and transmutation. Space disposal is discussed in Sections 1, 3, and 4. The discussions below are given to allow a comparison between the possible disposal systems and to estimate the cost related to these systems.

2.2.1 Geologic Disposal

The most attractive isolation method is to inter the waste in selected geologic formations. The waste is first processed and solidified, and then isolated from the biosphere by placing it in a stable geologic formation such as salt deposits, granite vaults, ice beds, or the ocean floor. These alternatives have been discussed in great detail;[2-3 through 2-8] the following will be only an overview of disposal in each of the geologic formations.

Of the disposal locations, salt beds are the closest to being used in this and other countries and are attractive because they are water free and when the salt is back-filled around the canister, it tends to reform into a solid structure. Currently, the Federal German Republic is placing low-level radioactive waste in the ASSE II salt mine near Wolfenbuttel. High-level waste could be stored there as early as 1978.[2-7]

The granite vault location would produce a situation very similar to the salt case except there would be no capability of the granite to reform a solid structure. The waste would, however, be in a location where it could be easily retrieved or monitored.

Disposing of the waste in the ice beds would involve placing the canister on the ice and would allow the decay heat from the waste to melt the ice to a predetermined depth. The ice would resolidify over the canister sealing it away from the biosphere. The ice would restrict the movement of the hazardous nuclides should they escape the canister. Disadvantages are the relative ease of retrievability by terrorists and the remote possibility of the ice caps melting.

The disposal of the waste in the ocean bed could involve the placement of the waste either in the accumulating sediment, in deep sea trenches, in the stable deep sea floor or in the zones where one crustal plate is moving over another causing the one plate to slip into the Earth's mantle. This method and the one involving ice beds would require international cooperation.

2.2.2 Transmutation

Transmutation involves the conversion of fission products and actinides to short-lived or stable nuclides by subjecting these materials to a high neutron flux. The flux could be produced by either a fission or fusion reactor. The advantage to the process is that the most hazardous nuclides are converted to less hazardous nuclides. There are several disadvantages to using this method: the efficiency of the reactor is decreased by the absorption of neutrons by non-fissile nuclides, and the waste nuclides need to be separated from the spent fuel and encapsulated for their introduction into the reactor, which causes extra capital cost at both the fuel processing plant and fuel fabrication plants. An indepth discussion of transmutation is found in BNWL-1900.[2-9]

2.2.3 Estimated Terrestrial Disposal Cost

Estimated costs have been developed for the various geologic disposal options. Table 2-5 shows a brief comparison of the various options. For example, the cost of disposing the waste in an ocean bed was estimated to be between \$14/kg to \$17/kg in 1973 dollars.[2-8] This cost was based on the amount of material processed and evaluated at the time of reprocessing. To obtain these values in terms of late 1976 dollars, a 22% escalation factor must be included to account for inflation.[2-10] This gives adjusted values of \$17–20/kg for ocean bed disposal. The cost in 1976 dollars of disposing waste in the ice beds is \$24–29/kg[2-8], while the cost of transmutation is about \$46/kg.[2-8] The cost of salt bed disposal has been thoroughly examined in a recent study which estimates the cost of waste disposal in salt formations to be between \$5 and \$10/kg.[2-10] The same report estimates the cost of disposing the waste in granite formations to range from \$11–15/kg. As can be seen from Table 2-5, salt beds are the least expensive method of disposal.

2.3 Waste Mixes

Partitioning waste with the eventual disposal of the most hazardous partitioned fraction in space can reduce the risk to man caused by the total HLW stream. The reasoning behind the desirability of partitioning is complex due to the number of tradeoffs available. Some of these tradeoffs are economic while some are technical. For example, it might be desirable to dispose of in space the transuranic alpha emitters whose long half-lives and toxicity suggest absolute removal from the biosphere. It might be desirable to remove those nuclides (e.g., curium-244) with short half-lives and high specific activity and heat content, allow them to decay for ~10 years and then dispose of them in space, thus reducing handling problems. Other options revolve around the most desirable weight fractions from the standpoint of minimum Space Shuttle launches. To evaluate all the possible partitioning options is beyond the scope of this report, therefore, five reasonable options were selected for study. These options are defined and some of the advantages and disadvantages of each are given in the next section. The effects of the partitioning options with the subsequent disposal in space of the partitioned section on a hazard index is discussed.

2.3.1 Definitions of Waste Mixes

Five waste mix options were defined for this study. The following subsections discuss these options and give insight to the respective advantages and disadvantages of each.

TABLE 2-5. COST OF VARIOUS TERRESTRIAL DISPOSAL METHODS IN 1976 DOLLARS

Method	Cost $/kg Reprocessed Fuel	Reference
Ice Bed	24-29	2-8
Ocean Bed	17-20	2-8
Transmutation	46	2-8
Granite Formation	11-15	2-10
Salt Formation	5-10	2-10

2.3.1.1 Option 1: The fuel is leached and the entire dissolver solution is solidified and shipped into space.

This mix is about one operation away from sending entire fuel bundles into space. The advantages to this scheme are: (1) fuel reprocessing would not be necessary, (2) plutonium proliferation would be no threat, and (3) the waste would be removed from the Earth. The disadvantages would be: (1) an enormous amount of waste would be sent into space requiring extremely large launch rates, and (2) the uranium and plutonium would be lost as future energy sources.

2.3.1.2 Option 2: 99.5% of the uranium is recovered from the dissolver solution. The remaining dissolver solution is solidified and sent into space.

The advantages for this mix are: (1) the uranium has been recovered for possible use as an energy source, (2) the threat of plutonium proliferation has been eliminated, (3) the bulk of the waste activity is removed from the Earth, and (4) the process uses fairly standard technology. The disadvantages are: (1) the plutonium is lost as a future energy source, and (2) the amount of material sent into space is still large.

2.3.1.3 Option 3: 99.5% of the uranium and plutonium are recovered from the dissolver solution. The remaining dissolver is solidified and sent into space.

The advantages for this mix are: (1) the uranium and plutonium have been recovered for possible use as energy sources, (2) the bulk of the waste activity has been removed from the Earth, and (3) standard technology is used to produce the mix. The disadvantages are: (1) plutonium proliferation is a possibility, and (2) the amount of material sent into space is relatively large, although not prohibitive.

2.3.1.4 Option 4: 0.1% of the uranium and plutonium, the balance of actinides, and all the rare earths except cerium are sent into space after solidification.

The advantages for this mix are: (1) the uranium and plutonium have been recovered for possible use as an energy source, (2) most of the long half-life materials are sent into space, and (3) the amount of material being sent into space is small. The disadvantages are: (1) plutonium proliferation is a threat, (2) some of the fission products are left on Earth, and (3) the separation process uses techniques that are not fully proven.

2.3.1.5 Option 5: 99.5% of the uranium and plutonium and 94% of the technetium are recovered from the dissolver solution. The technetium is sent into space after solidification.

The advantages for this mix are: (1) the amount of waste shipped into space is very small, (2) the uranium and plutonium are available as future energy sources, and (3) this extremely mobile and toxic nuclide is placed in the safest possible location from the viewpoint of

mankind. The disadvantages are: (1) the threat of plutonium proliferation is possible, and (2) the majority of the radioactive waste remains on Earth. In a study on incentives for partitioning, Burkholder, et al,[2-11] concluded that there was some incentive to partitioning technetium from the waste. Using this recommendation, this mix was selected for consideration.

2.3.2 Relative Hazards of the Partitioning Options

It is extremely difficult to estimate the relative merits of partitioning. The following will be an attempt to show the effects on a defined hazard index. The index used is the amount of water required to dilute each nuclide to the allowed limit as defined in Appendix B, Table II of 10CFR20.[2-13] To simplify this process, the required water for the limiting isotope for each element was used to determine the hazard index for that element. This will cause the hazard index to be conservative. After the initial partitioning, the capability of various daughter nuclides to be formed is reduced within the mix from which the parent is removed, but in generating the hazard index for each option, it was assumed that the daughter nuclides were formed at a rate proportional to the amount of original precursors present in the dissolver solution. This assumption is also conservative. Thus, the generated tables are only indicative of the effects of partitioning. Table 2-6 gives the total amount of water required to reduce all nuclides to the acceptable levels. The amount of water is the sum of all the water required for each element. The amount of water required for both the terrestrial and space disposal fractions are given. Table 2-7 gives the fraction of the total hazard index present in the terrestrial and space disposal fraction. Both the tables give the hazard index as a function of time since reactor discharge and of the partitioning option. Table 2-8 shows how much of the original dissolver hazard index is remaining at various times after reactor discharge.

Table 2-7 shows that only Options 1 and 2 have higher space hazard indices than Earth indices. These both dispose of the plutonium in space. Using the preceeding index, it was found that plutonium controlled the index, therefore, the disposal mix that contains the plutonium will have the higher index. The type of index used is not one that gives adequate information on the total effects of partitioning. To develop a method to determine the actual effects of each option would be a major task, much beyond the scope of this work.

2.4 Partitioning

This section will discuss briefly the definition and history of partitioning and then go into detail on the development of five partitioning options. Flowsheets have been developed which should result in the mixes which have been defined in Section 2.3.

2.4.1 Definition and History

Partitioning is the systematic removal of selected nuclides from a mixture of nuclides. The purpose of the removal may be economic or to reduce the hazard of the waste. Previously, the partitioning that has been done was for economic reasons, although partitioning of waste is currently thought of to reduce the risk to man.

Fuel reprocessing is really partitioning in that it recovers uranium and plutonium from the fission products for use as reactor fuels. Almost any element can be recovered using certain

TABLE 2-6. HAZARD INDEX FOR THE VARIOUS OPTIONS (m^3H_2O)

Option	Disposal Site	Years After Discharge 1/2	1,000	10,000	100,000
1*	Earth	--	--	--	--
	Space	4.18E+11	6.3 E+8	4.38E+8	5.13E+7
2	Earth	1.48E+6	3.48E+6	4.28E+6	1.11E+7
	Space	4.18E+11	6.26E+8	4.33E+8	4.02E+7
3	Earth	2.93E+10	6.05E+8	4.3 E+8	4.4 E+7
	Space	3.9 E+11	2.66E+7	8.6 E+6	7.3 E+6
4	Earth	3.75E+11	6.07E+8	4.31E+8	4.5 E+7
	Space	4.3 E+10	2.31E+7	6.12E+6	6.24E+6
5	Earth	4.18E+11	6.3 E+8	4.38E+8	5.11E+7
	Space	2.68E+5	2.68E+5	2.6 E+5	1.93E+5

*For Option No. 1, should the waste be stored on Earth, the hazard index values for "Space" apply.

TABLE 2-7. FRACTION OF HAZARD INDEX FOR EACH OPTION

Option	Disposal Site	Years After Discharge 1/2	1,000	10,000	100,000
1	Earth	--	--	--	--
	Space	1.0	1.0	1.0	1.0
2	Earth	--	0.01	0.01	0.22
	Space	1.0	0.99	0.99	0.78
3	Earth	0.07	0.96	0.98	0.86
	Space	0.93	0.04	0.02	0.14
4	Earth	0.90	0.96	0.99	0.88
	Space	0.10	0.04	0.01	0.12
5	Earth	1.0	1.0	1.0	1.0
	Space	--	--	--	--

TABLE 2-8. DECREASE OF HAZARD INDEX DUE TO DECAY

Years After Discharge	Fraction of Original Hazard Index Remaining
1/2	1.0
1,000	0.0015
10,000	0.0010
100,000	0.0001

processing methods including solvent extraction, ion exchange, and other specialized separation techniques. Table 2-9 shows various nuclides and some references concerning the partitioning of the listed nuclides. The table is a small sample of the large amount of literature available on the recovery of these nuclides. A basic discussion of partitioning was presented in BNWL-1900,[2-34] and a recent workshop on waste partitioning[2-35] gives an excellent overview of partitioning. There has been much work done dealing with partitioning including analyzing the incentives to partitioning in terms of health effects[2-36] and analyzing the feasibility of partitioning.[2-38,2-39]

In this study, partitioning followed by space disposal of selected nuclides can potentially reduce the hazard to man of high-level waste. The ideal partitioning scheme would yield optimal terrestrial and space disposal mixtures. Although the optimal mixes can only be determined by detailed work, the mixes picked for this study are logical choices for examination.

2.4.2 Flowsheets for Waste Mix Options

Flowsheets were developed to show that the HLW could be partitioned into relatively small high risk fractions which will be feasible for space disposal. The options examined cover a large range of final disposal waste quantities, from the entire solidified dissolver solution to only the technetium. The amount of waste nuclides disposed in space for the various options are discussed. A preliminary estimate of the cost of the various flowsheets was developed. The flowsheet work uses processes found in open literature, but this does not insure that the processes will work. Each option will have to be proven experimentally prior to actual operation.

2.4.2.1 Process Flowsheet Description

Process flowsheets were developed for five options that would produce various waste fractions for space disposal. The options are assumed to process spent fuel after a 1/2 year cooling down period. Figures 2-1 through 2-5 show simple process flowsheets for each option which are briefly described below. The five options are:

- Option 1. The spent fuel is chopped and leached. The dissolver solution is solidified for space disposal.
- Option 2. The dissolver solution is processed to recover 99.5% of the uranium. The balance of the solution is solidified for space disposal.
- Option 3. The dissolver solution is processed to recover 99.5% of the uranium and plutonium. The balance of the solution is solidified for space disposal.
- Option 4. The dissolver solution is processed to recover 99.9% of the uranium and plutonium. The actinides present in the waste solution, which includes 0.1% of the dissolver solution uranium and plutonium, and the rare earth fission products other than cerium are solidified for space disposal. The other fission products are disposed terrestrially.
- Option 5. The dissolver solution is processed to recover 99.5% of the uranium and plutonium. The technetium is extracted and solidified for space disposal and the balance of the solution is disposed terrestrially after solidification.

TABLE 2-9. RECOVERY TECHNIQUES

Element	Reference
Actinides	2-15, 2-16, 2-17
Americium	2-18
Cerium	2-13, 2-14, 2-19, 2-20
Cesium	2-13, 2-14, 2-21, 2-22
Curium	2-18, 2-23, 2-25
Molybdenium	2-25
Neptunium	2-24, 2-29, 2-30
Plutonium	2-26, 2-27, 2-28
Promethium	2-13, 2-14, 2-31, 2-32
Rare Earths(RE)	2-15
Ruthenium	2-13
Strontium	2-13, 2-14, 2-21, 2-33
Technetium	2-13, 2-14
Uranium	2-26, 2-27, 2-28
Zirconium-Niobium	2-13

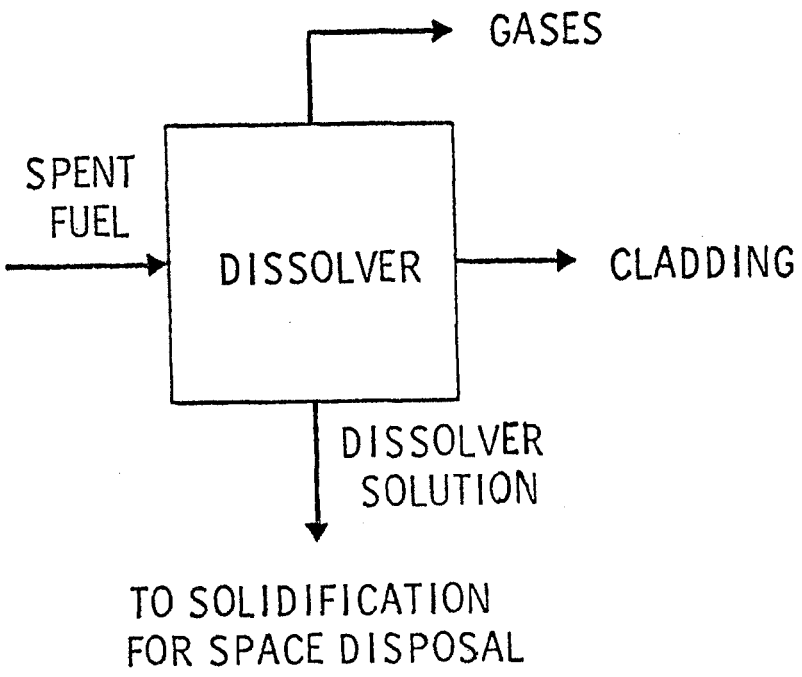

FIGURE 2-1. OPTION 1

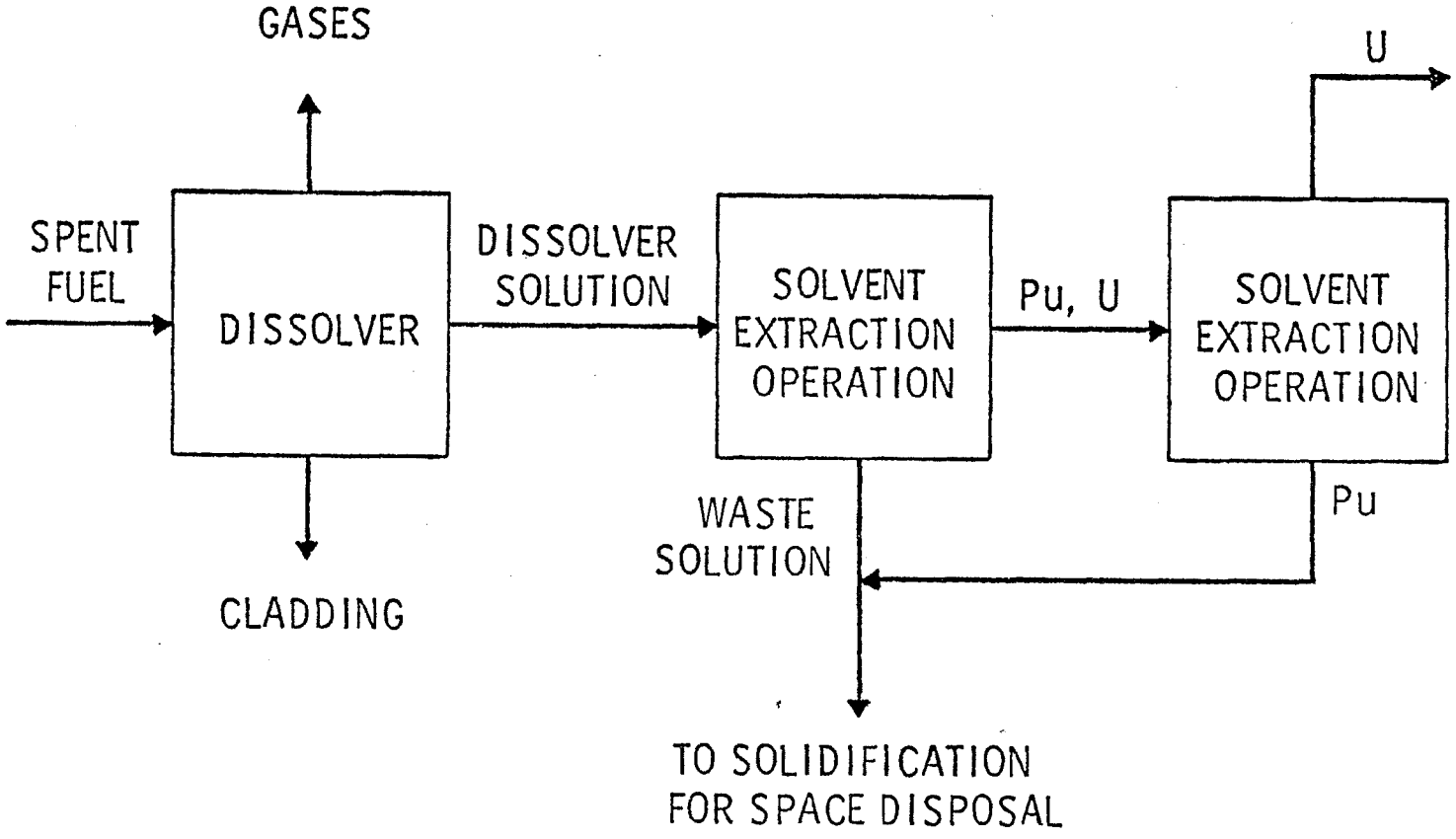

FIGURE 2-2. OPTION 2

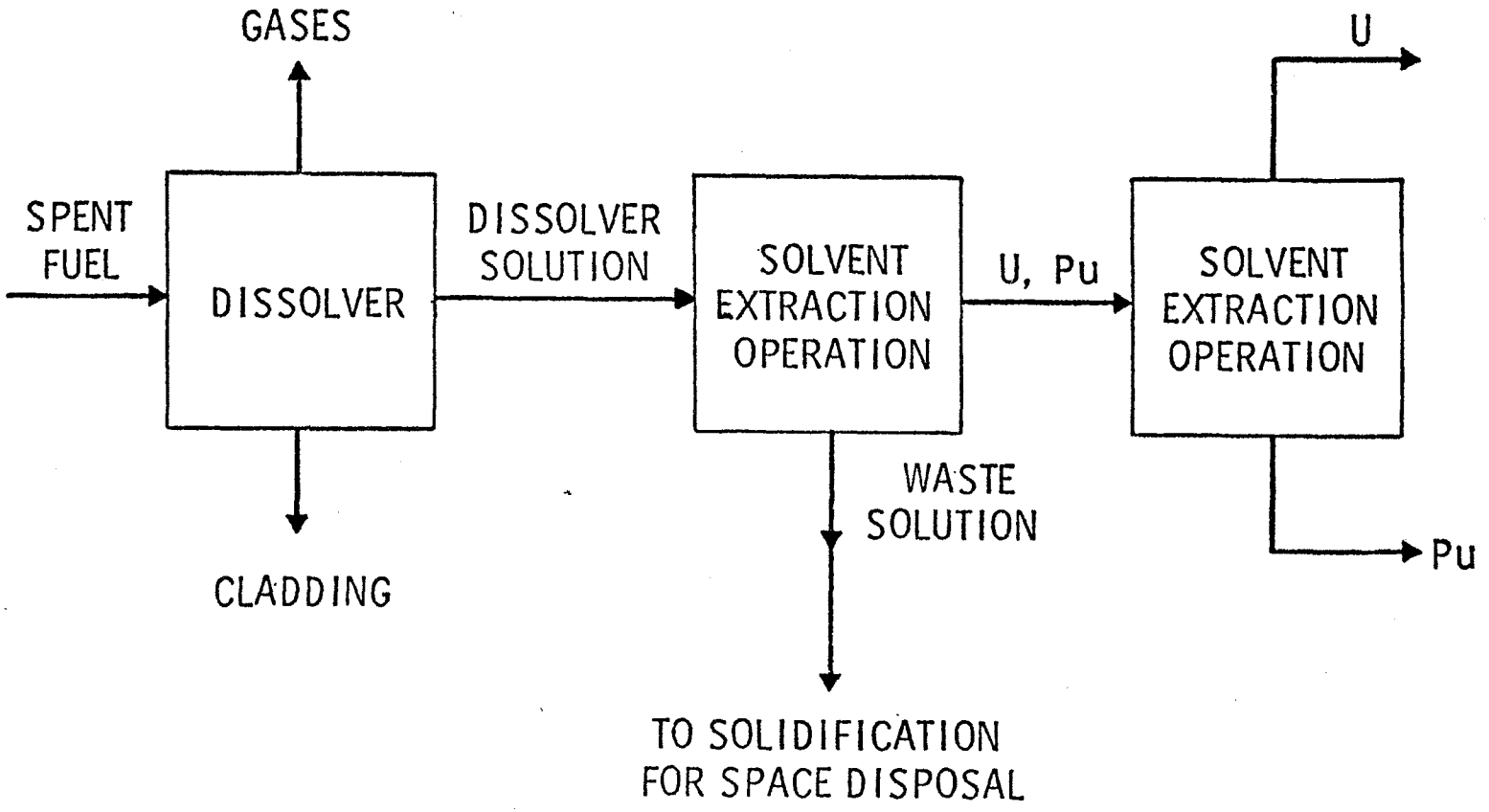

FIGURE 2-3. OPTION 3

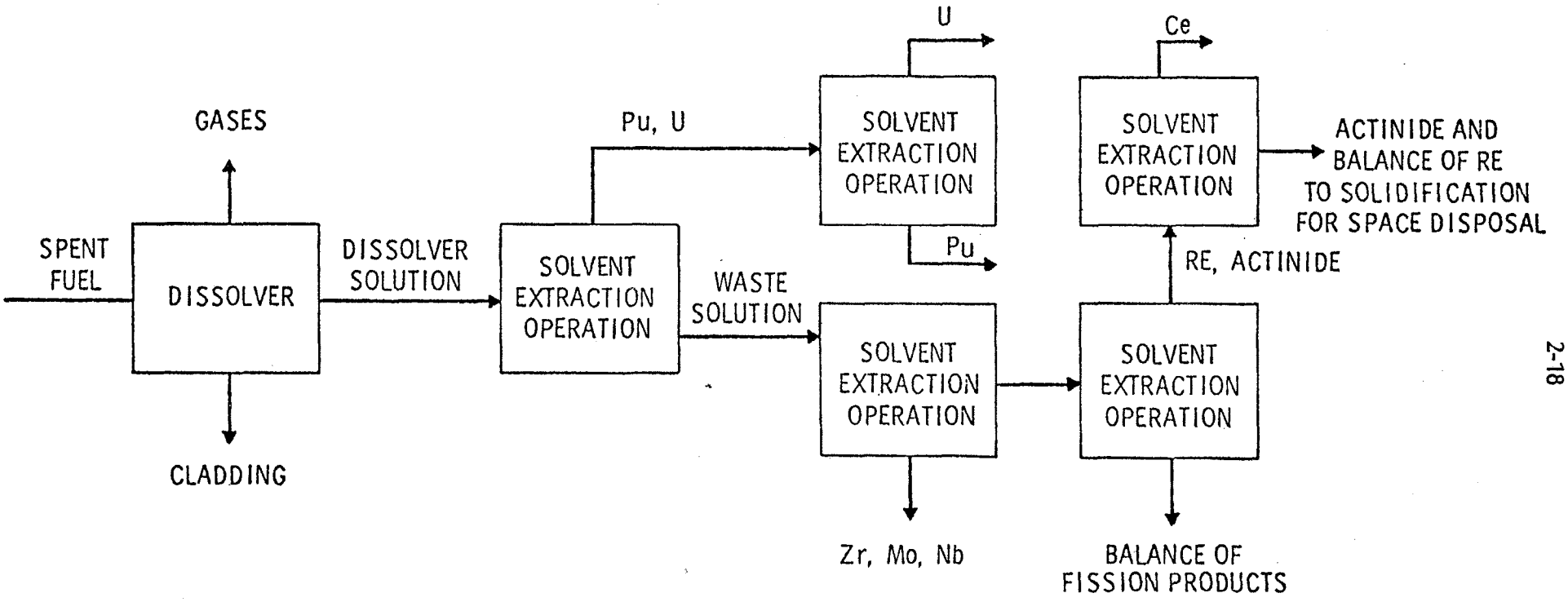

FIGURE 2-4. OPTION 4

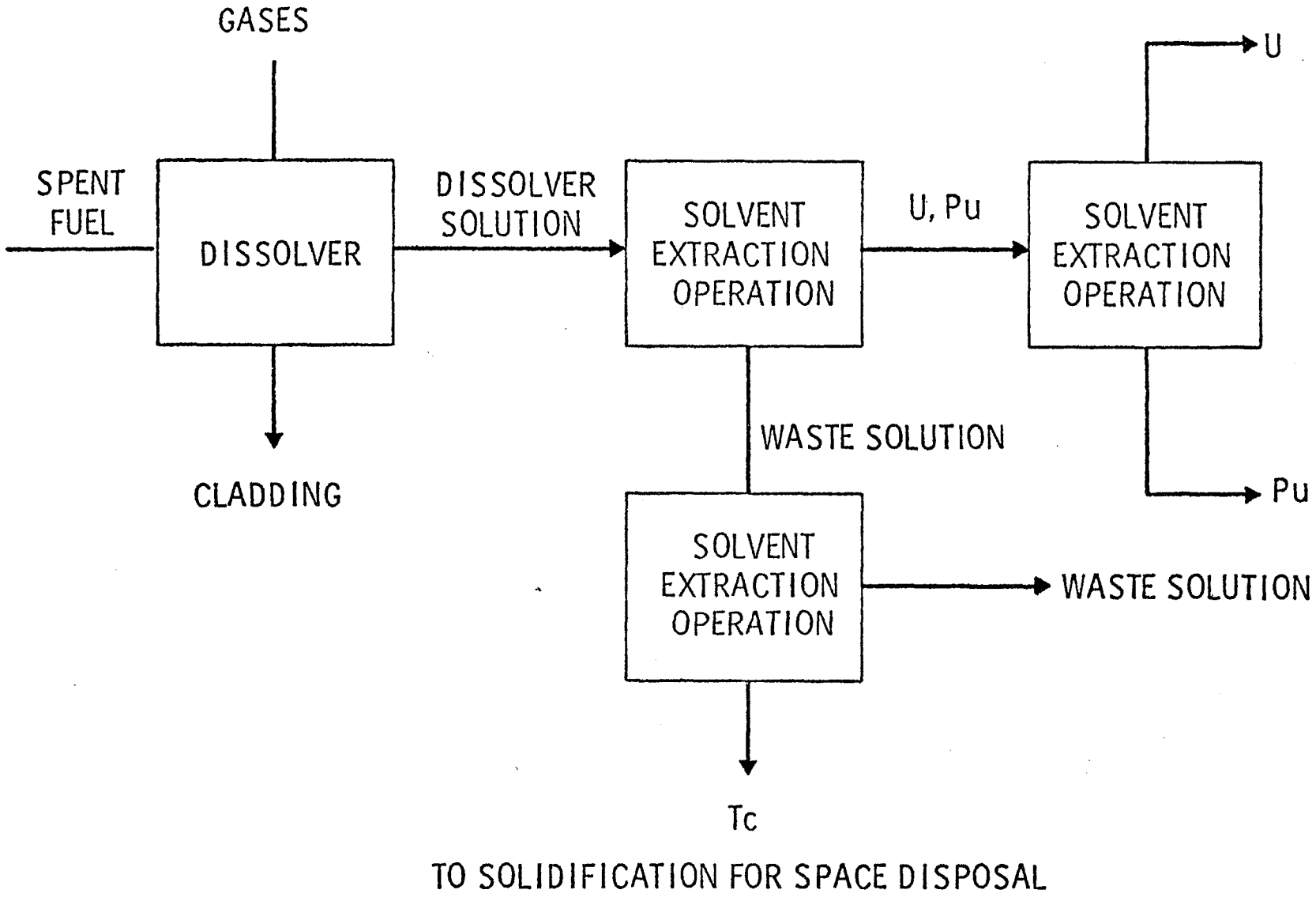

FIGURE 2-5. OPTION 5

Table 2-10 shows the assumed elemental distribution calculated by the ORIGEN code to be in the dissolver solution; the fission gases are not present in the solution. It was assumed that the dissolved spent fuel had a burnup of 33,000 MWd/MT and the original fuel contained no recycled material. This distribution shows the relevant amount of each nuclide found in the spent fuel.

2.4.2.1.1 Option 1

Option 1 consists of taking the spent fuel rods and leaching out the contained fuel using 2.5M HNO_3. The fission gases are released and handled in the fuel reprocessing plant offgas system. The remaining fission products and actinides are solidified for space disposal.

2.4.2.1.2 Option 2

Option 2 is a variation of the Purex process (Option 3). Plutonium and uranium are partitioned in the IBX Column. The aqueous plutonium stream is then scrubbed in the IBS Column. The residual uranium is removed from the aqueous stream and is recycled to the HA Column. The aqueous plutonium stream is then combined with the aqueous stream from the HA Column and is solidified for space disposal. The balance of the process is similar to the uranium portion of Option 3. Figure 2-6 illustrates the overall process and the assumed performance of the process is shown in Table 2-11.

2.4.2.1.3 Option 3

Option 3 (the Purex process) is assumed to be the reference case since it is the normal process planned for use at commercial fuel reprocessors. Table 2-12 shows the assumed performance of Option 3. Tributyl phosphate (TBP) is used as a solvent to selectively extract uranium (VI) and plutonium (IV) from the dissolver solution. The neptunium is prevented from being extracted by stabilizing the neptunium in the (V) valence state using sodium nitrite in the HA Column. This extraction process, shown in Figure 2-7, consists of a first decontamination and partitioning cycle and subsequent uranium and plutonium cycle.

Since the Purex process is well documented,[2-39 through 2-41] only an overview of the process will be given here. The dissolver solution is introduced into the HA Column where the bulk of the uranium and plutonium are extracted by 30% TBP-normal parafin hydrocarbon (NPH) organic phase. The bulk of the fission products remain in the aqueous phase. In the HS Column, the uranium and plutonium are further decontaminated by contacting the organic phases with a HNO_3 stream. The loaded organic phase is then contacted in the IBX Column with an acidic solution containing hydrazine and hydroxylamine nitrate (or other reducing agent) to reduce the Pu (IV) to Pu (III), which is virtually insoluble in TBP. In this manner the plutonium is separated from the uranium.

The two product streams are then put through separate purification cycles. The aqueous plutonium is contacted in the IBS Column with another organic stream to further separate it from any residual uranium which is then returned to the HA Column. The plutonium rich stream is further decontaminated in subsequent solvent extraction cycle steps. The organic uranium stream is stripped using a dilute acid solution in the IC Column, then the aqueous solution is concentrated. The stream is introduced to other uranium purification steps. The final solution is then concentrated and stored for later conversion to uranium oxide. The aqueous stream from the HA Column is the stream solidified for space disposal.

TABLE 2-10. NUCLIDE INVENTORY OF DISSOLVER SOLUTION BASED ON MT HEAVY METAL AFTER 6-MONTH COOLING PERIOD(1)

Nuclide	Grams	Wt Fraction	Watts	Thermal Load Fraction
Ge	0.374	3.76E-7	0.	0.
As	0.0846	8.5E-8	0.	0.
Se	51.6	5.19E-8	1.50E-4	8.34E-9
Rb	327.	3.29E-4	2.69E-3	1.5E-7
Sr	873.	8.78E-4	307.	1.71E-2
Y	458.	4.6E-4	829.	4.61E-2
Zr	3630.	3.65E-3	976.	5.43E-2
Nb	9.27	9.32E-6	1760.	9.76E-2
Mo	3540.	3.56E-3	1.23E-16	6.84E-21
Tc	841.	8.45E-4	9.68E-3	5.38E-7
Ru	2300.	2.31E-3	184.	1.02E-2
Rh	386.	3.88E-4	4170.	0.232
Pd	1380.	1.39E-3	9.75E-6	5.42E-10
Ag	63.4	6.37E-5	42.9	2.39E-3
Cd	90.6	9.11E-5	0.121	6.73E-6
In	1.24	1.25E-6	8.17E-4	4.54E-8
Sn	53.5	5.38E-5	11.3	6.29E-4
Sb	17.6	1.77E-5	33.2	1.85E-3
Te	573.	5.76E-4	22.1	1.23E-3
Cs	2700.	2.71E-3	2420.	0.135
Ba	1410.	1.42E-3	393.	2.19E-2
La	1270.	1.28E-3	1.42	7.06E-2
Ce	2680.	2.69E-3	600.	3.34E-2
Pr	1220.	1.23E-3	5200.	0.289
Nd	3910.	3.93E-3	0.0204	1.13E-6
Pm	97.7	9.82E-5	69.8	3.80E-3
Sm	819.	8.23E-4	2.16	1.2E-4
Eu	189.	1.9E-4	65.3	3.63E-3
Gd	122.	1.23E-4	0.0335	1.06E-6
Tb	1.9	1.91E-6	2.01	1.12E-4
Dy	1.17	1.18E-6	6.25E-19	3.40E-23
Ho	0.115	1.16E-7	8.93E-6	4.97E-10
Er	0.0359	3.61E-8	0.	--
Tl	1.81E-12	1.82E-18	1.23E-5	6.84E-10
Pb	4.86E-7	4.89E-13	2.1E-6	1.17E-10
Bi	1.41E-10	1.42E-16	2.55-5	1.42E-9
Po	3.65E-14	3.67E-20	1.1E-4	6.12E-9
At	1.2E-20	1.21E-26	8.15E-10	4.53E-14
Fr	2.59E-16	2.6E-22	7.37E-10	4.1E-14
Ra	1.39E-8	1.4E-14	5.01E-5	2.79E-9
Ac	5.61E-9	5.64E-15	8.74E-10	4.86E-14
Th	5.49E-4	5.52E-10	1.71E-4	9.51E-9
Pa	1.57E-4	1.58E-10	2.07E-3	1.15E-7
U	956,000	0.961	0.0224	1.25E-6
Np	475.	4.77E-4	0.0386	2.15E-6
Pu	9,100.	9.15E-3	128.	7.12E-3
Am	164.	1.65E-4	6.78	3.77E-4
Cm	45.	4.52E-5	754.	4.19E-2
Bk	2.27E-6	2.28E-12	9.45E-7	5.26E-11

(1) Obtained from ORIGEN computation, 33,000 MWd/T burnup, no fuel recycle.

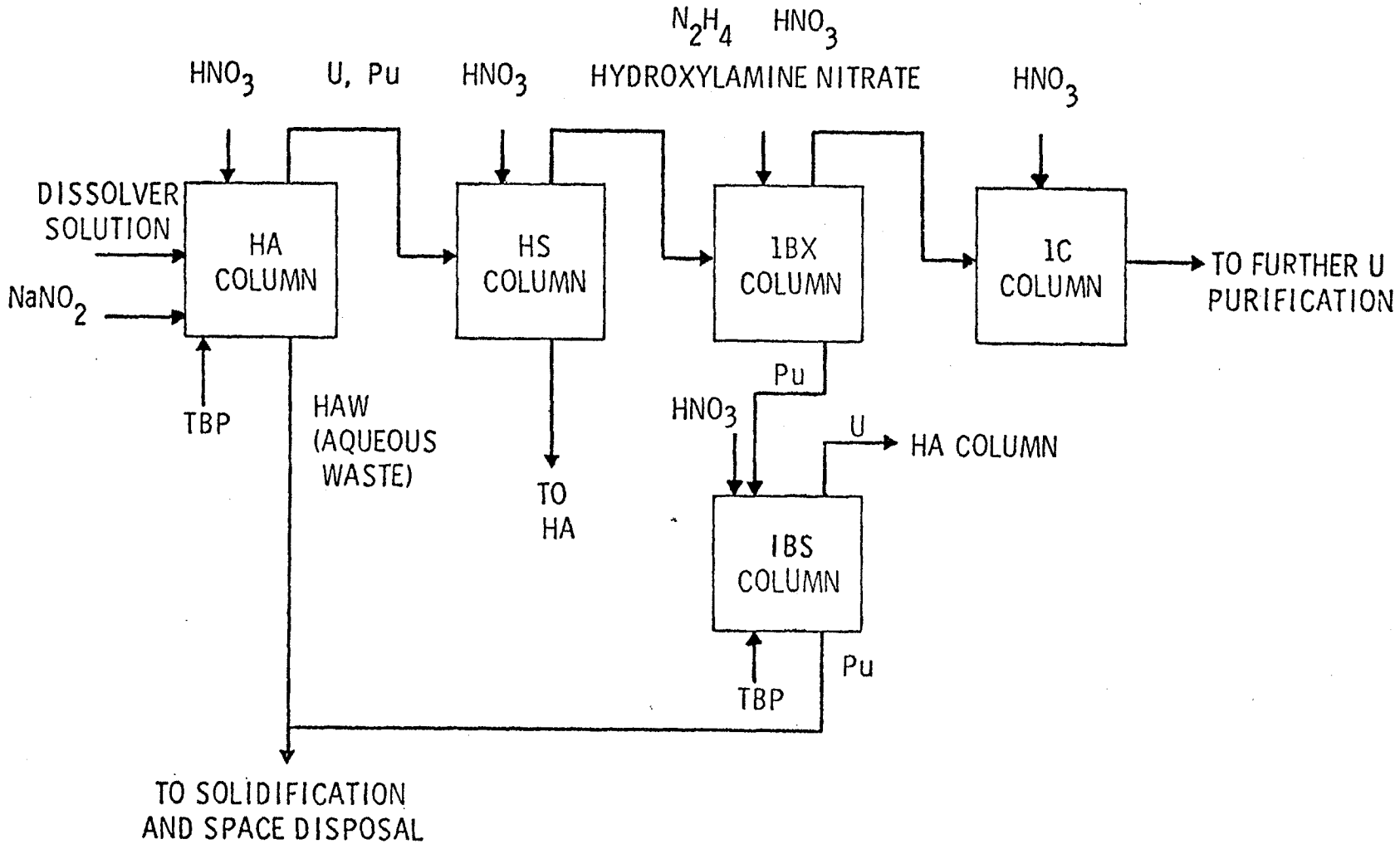

FIGURE 2-6. OPTION 2

TABLE 2-11. ASSUMED PLANT PERFORMANCE OF OPTION 2

Step	Separation
Separation of plutonium from uranium	$10^{6(2-41)}$
Decontamination of fission products from uranium	$10^{7(2-41)}$
Uranium recovered	99.5%
Separation of neptunium from uranium	95%

TABLE 2-12. PILOT PERFORMANCE OF OPTION 3

Step	Separation
Separation of uranium from plutonium	$>10^{7(2-41)}$
Separation of plutonium from uranium	$10^{6(2-41)}$
Decontamination of fission products from plutonium	$>10^{8(2-41)}$
Decontamination of fission products from uranium	$10^{7(2-41)}$
Plutonium and uranium recovered	99.5%
Separation of neptunium from plutonium	∿100%
Separation of neptunium from uranium	95%
Separation of plutonium from uranium	$10^{6(2-41)}$
Decontamination of fission products from uranium	$10^{7(2-41)}$
Uranium recovered	99.5%
Separation of neptunium from uranium	95%

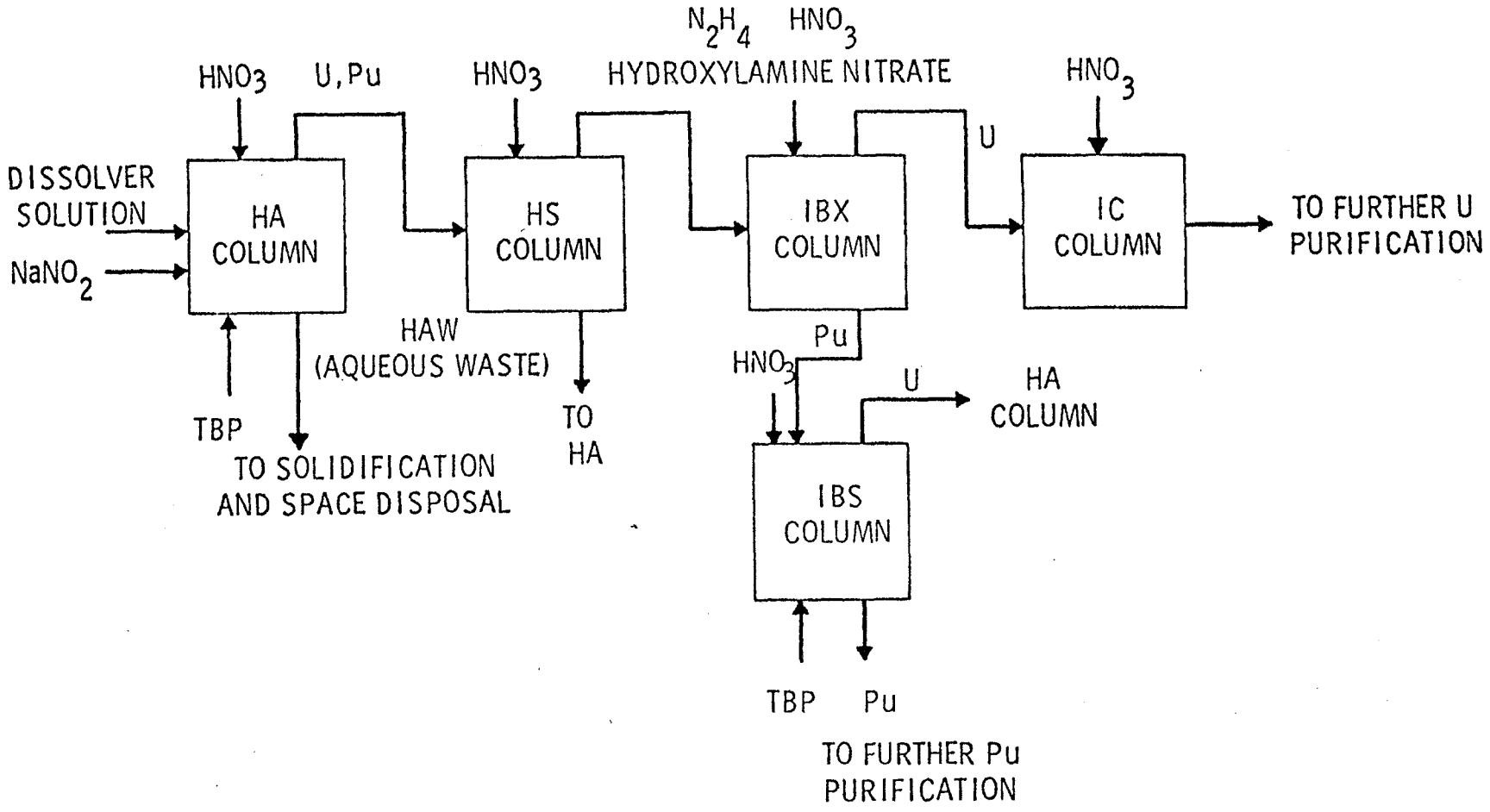

FIGURE 2-7. OPTION 3
(Referenced Purex Process)

2.4.2.1.4 Option 4

Option 4 is the most complex flowsheet and is illustrated in Figure 2-8. It consists of a series of partitioning steps, each separating nuclides or sets of nuclides. The flowsheet uses TBP, di (2-ethylhexyl) phosphoric acid (HDEHP) and a mixture of the two. The front end of Option 4 is the complex Purex process as described in Option 3. The fission product waste from Option 3 is further processed to remove its zirconium, niobium and molybdenum content to allow good separation of the rare earths and actinides from the fission product in a subsequent step. Zirconium, molybdenum and niobium would tend to follow the rare earths in the latter extraction process if they were allowed to remain in the process stream. The waste stream is concentrated from 4.5M to 6M HNO_3 which is a form acceptable for extraction. Then, any solids that are formed are removed by centrifuging. The zirconium and molybdenum are then extracted in a column using 0.6M di(2 ethylhexyl) phosphoric acid (HDEHP) in a kerosene dilutent as extractant and 6M HNO_3 as the scrubbing fluid. The scrub removes the actinides which had extracted into the organic phase. The organic containing the zirconium and molybdenum is contacted with an aqueous solution to strip the molybdenum and zirconium which is then concentrated and stored for terrestrial disposal. The zirconium-molybdenum free waste stream is in a form unacceptable for the separation of the rare earths and actinides from the rest of the fission products. The nitrate concentration in the stream needs to be reduced from 6M to about 0.01M. This is accomplished by the use of sugar or formic acid. The stream is then processed to remove any solids that might have been formed. The low acid stream is then contacted with a 0.6M HDEHP organic phase. The rare earths and actinides are extracted into this organic phase leaving the other fission products in the aqueous phase. The rare earth and actinides are removed from the organic phase by stripping it with a 6.5M nitric acid solution.

The rare earths and actinides are now essentially separated from the other constituents of the waste. The final step is to remove the cerium from the mixture. The stream is adjusted to 2M HNO_3 and sufficient $K_2S_2O_8$ and $AgNO_3$ are added to adjust the solution to 0.02M $AgNO_3$ and 0.2M $K_2S_2O_8$. The adjusted stream is then contacted with a 0.4M HDEHP, 0.2M TBP-NPH diluent organic phase where the cerium is extracted into the organic phase. The cerium is separated due to the fact that $K_2S_2O_8$ and $AgNO_3$ cause the cerium (III) to oxidize to the IV state. The aqueous phase is then processed to recover its silver content and then solidified for disposal in space.

The cerium-rich organic phase is contacted with a dilute acid phase containing a reducing agent. The cerium (IV) is reduced to cerium (III) and is stripped into the aqueous phase. The aqueous phase is concentrated and stored along with the other extracted fission products. The assumed performance of this option is shown in Table 2-13.

2.4.2.1.5 Option 5

Option 5 is the extraction and space disposal of only the technetium. Technetium will be extracted from the HLW after the uranium and plutonium are removed as described for Option 3; see Figure 2-9 for an illustration of this process, and see Table 2-14 for the assumed performance for this option. The technetium present in the waste will be in the form of a pertechnetate ion (TcO_4) .[2-40] The waste system is about 4.5M HNO_3. For the solvent extraction of technetium from a nitric acid solution, the nitric acid concentration needs to be about 0.7M which is accomplished by sugar denitration. The solution is then centrifuged to remove any solids formed. The stream is then contacted with a TBP-containing organic stream to extract the technetium; a distribution coefficient of about 50 is easily achievable.[2-49,2-50] The

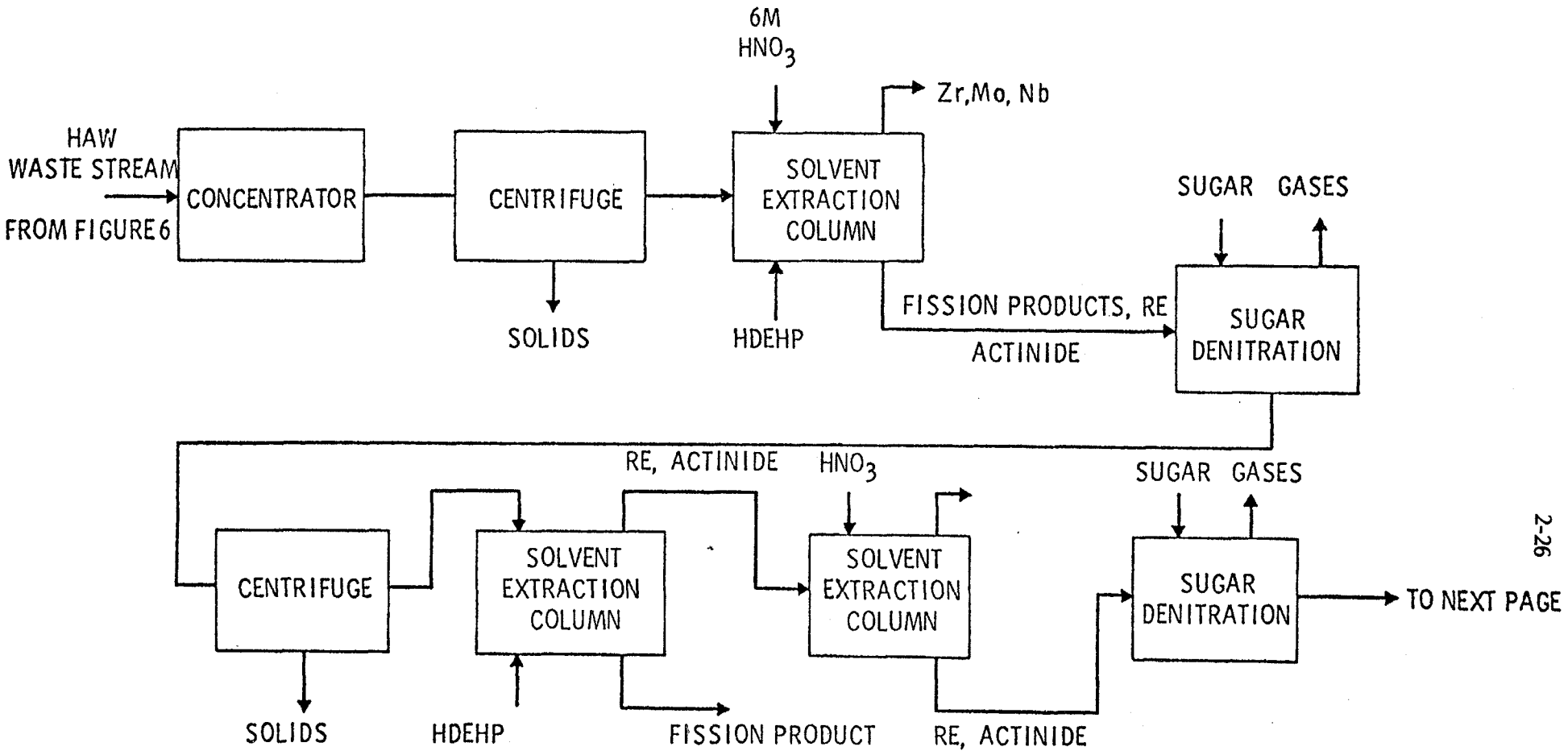

FIGURE 2-8. OPTION 4

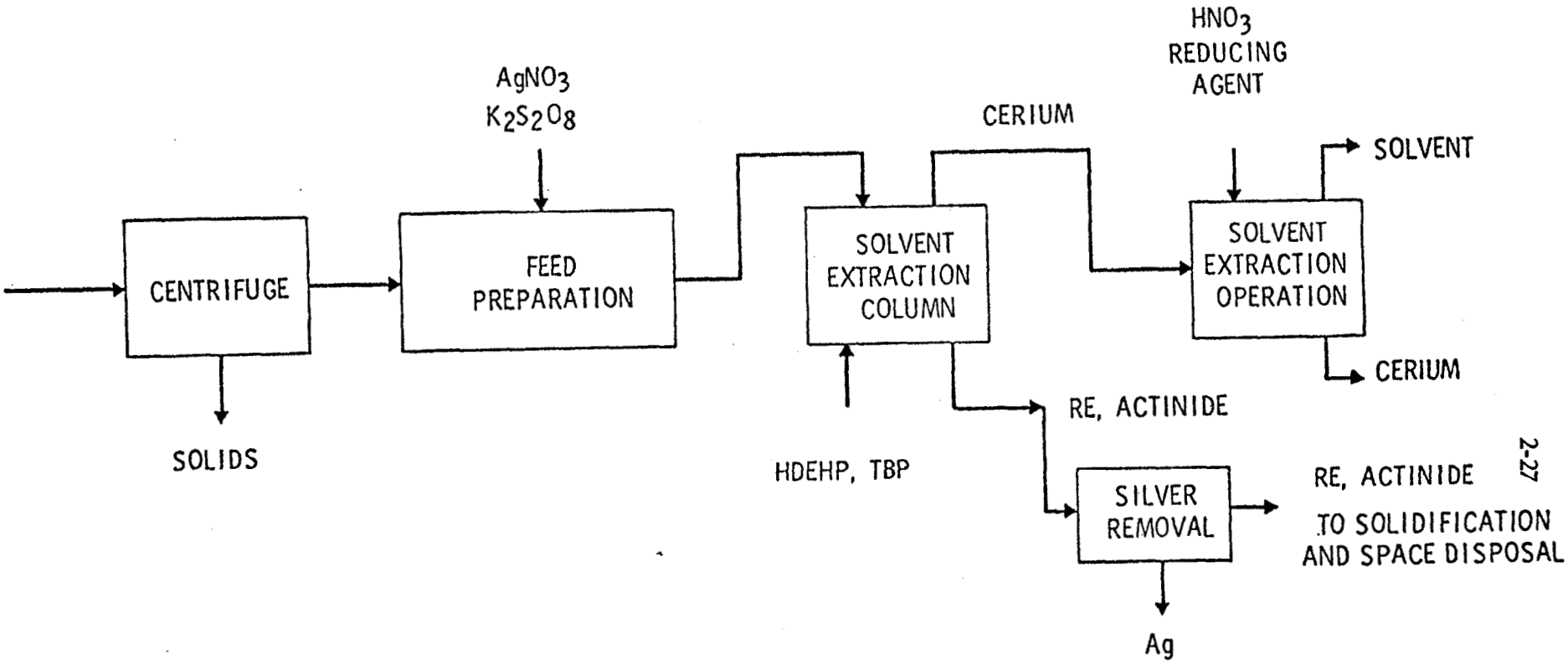

FIGURE 2-8. OPTION 4 (Continued)

TABLE 2-13. ASSUMED PERFORMANCE OF OPTION 4

Step	Separation
Separation of uranium from plutonium	$>10^{7}$ (2-41)
Separation of plutonium from uranium	10^{6} (2-41)
Decontamination of fission products from plutonium	$>10^{8}$ (2-41)
Decontamination of fission products from uranium	10^{7} (2-41)
Plutonium and uranium recovered	99.5%
Separation of neptunium from uranium	95%
Separation of neptunium from plutonium	∿100%
Separation of molybdenum from RE, actinides, fission product	∿100% (2-43)
Separation of zirconium from RE, actinides, fission product	∿100% (2-43)
Separation of fission product from RE, actinides	∿100% (2-44)
Separation of cerium from RE, actinides	∿99.4% (2-43)
Separation of actinides and RE from fission products	∿99%

TABLE 2-14. ASSUMED PERFORMANCE OF OPTION 5

Step	Separation
Separation of uranium from plutonium	$>10^{7}$ (2-41)
Separation of plutonium from uranium	10^{6} (2-41)
Decontamination of fission products from plutonium	$>10^{8}$ (2-41)
Decontamination of fission products from uranium	10^{7} (2-41)
Plutonium and uranium recovered	99.5% (2-41)
Separation of neptunium from plutonium	100%
Separation of neptunium from uranium	95%
Separation of technetium from fission product	∿98%
Total recovery technetium	∿94%

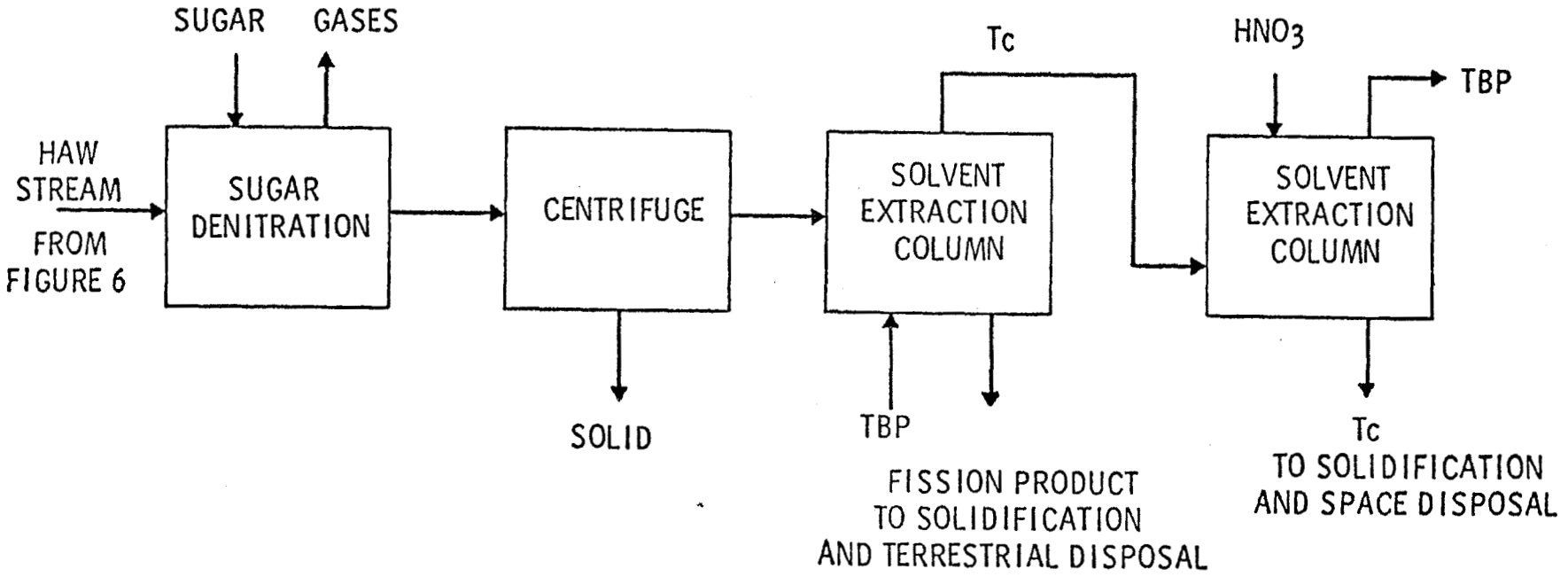

FIGURE 2-9. OPTION 5

back extraction of technetium from the organic requires the use of a high acid concentration (10M). The extraction system has not been proven; it requires more work to show that this method would suffice. By using TBP, the process is one that would combine well with Option 3. The aqueous technetium stream is then solidified for space disposal.

2.4.2.2 Weight and Heat Loads of Options

Due to partitioning, the weight of the waste nuclides and their decay heat is less than the original dissolver solution. Table 2-15 shows the weight and heat loads for each of the options. The ratio of each option to the dissolver solution for both weight and heat load are shown. The weight shown is the weight of the waste nuclides.

During processing, various inerts are added to the process stream. To be practical for space disposal, the streams have to contain a minimum of inerts. The amount of inerts found in a Barnwell-type waste is about 36 kg/MT heavy metal charged to reactor.[2-51] By the use of hydrazine and hydroxlamine nitrate as reducing agents and the use of geometric consideration instead of gadolinium nitrate for criticality control, the amount of inert added to the waste streams for Options 2 and 3 is about 7.2 kg/MT heavy metal. Option 1 is considered to have no inerts in the stream being solidified. Option 4 is assumed to contain about 1.5 kg of inert materials/MT heavy metal charged to the reactor with Option 5 containing 0.5 kg/MT.

The solidified waste multiplication factors given in Section 2.1 include the above amount of inert material.

2.4.2.3 Capital Costs of Options

An extremely simplified approach was used to arrive at rough capital cost estimates for each of the options considered. First, the capital expense was broken down into four components: structural, process equipment, bulk materials (pipe, valves, wire, etc.) and site improvement; Table 2-16 shows the estimated capital breakdown for these items. The plant was then broken down into regions where each of the above costs are valid; the breakdowns estimated for the various components are shown in Table 2-17.

Since the assumed area for the total structure for Option 3 (the reference case) is 6,200 m^2, the process area is 2,460 m^2 and the bulk area is 2,960 m^2. It is assumed that each cell has an area of 570 m^2. Exxon's capital cost estimate for a fuel reprocessing plant in January of 1976 was \$0.6B*. By using this value and the information presented in Table 2-17, the cost per square meter of the low cost components can be obtained. These values are shown in Table 2-18. The cost of the other captions can be roughly estimated by using the data in Table 2-18 and information provided in the following list. Table 2-19 summarizes the estimated cost factors for the five options.

* Exxon Construction permit application for Nuclear Fuel Reprocessing Plant, January, 1976.

TABLE 2-15. SPACE WEIGHT AND HEAT LOAD PER MT HEAVY METAL CHARGED TO REACTOR

Option	Weight Fraction of Dissolver Solution Nuclides	Nuclide Weight, g	Fraction of Dissolver Solution Heat Load	Solution Heat Load, W
1	1.0	9.94E+5	1.0	17,978
2	0.044	4.37E+4	0.999	17,977
3	0.035	3.46E+4	0.993	17,851
4	0.009	9.3 E+3	0.339	6,103
5	0.0008	790	5 E-7	0.009

TABLE 2-16. CAPITAL COST BREAKDOWN FOR FUEL REPROCESSING PLANT

Component	Percent of Total Cost
Structural Materials	30
Process Equipment	30
Bulk Materials	35
Site Improvement	5

TABLE 2-17. PERCENT OF REPROCESSING PLANT AREA AFFECTED BY THE COST COMPONENT (2-52)

Cost Section	%
Structural Materials	100.
Process Equipment	40.4
Bulk Materials	48.5

- Option 1 consists only of a dissolver section, but due to shielding and liquid handling facilities, it is assumed that half of the total process area remains in the plant. This gives a cost factor [cost of option plant/cost of reference plant (Option 3)] of 0.593.
- Option 2 is missing a cell, therefore, we subtracted 680 m^2 from the areas used in calculating the structural, process equipment, and bulk material cost. This gives a cost factor of 0.784.
- Option 3 is the reference plant, therefore, its cost factor is 1.0.
- Option 4 contains three additional process cells, therefore, 2,045 m^2 is added to each of the plant component areas. This gives a cost factor of 1.446.
- Option 5 has one additional cell, therefore, 680 m^2 is added to each plant component resulting in a cost factor of 1.168.

2.5 Solidified Waste Forms

This section discusses the current solid forms being developed for terrestrial disposal so that they can be evaluated for space disposal. Three sections will be devoted to looking at these materials options. The solid waste options are broken down into three categories: (1) calcines, (2) composites, and (3) glasses. The options are characterized by having binary waste oxide contents of greater than 75 percent for the calcines, 50–70 percent waste oxide for the composites, and less than 50 percent for the glasses. Table 2-20 shows the waste forms which belong to each of the three classes. Each form in each of the three categories will be explored in the first three subsections for physical and chemical properties, feasibility as an end product, and compatibility with containment structures. Advantages and disadvantages for the various forms will also be outlined. For application in space, the less inert material being launched the better; therefore, the waste loading characteristics are explored. The thermal conductivity of the forms also helps determine which waste forms are the most practical. Good heat transfer capabilities are required to keep the waste package thermally stable. The fourth subsection discussed the capital cost in the solidifying of the waste, while a fifth section explains the possibilities of using other basic waste compounds for the retention of waste nuclides. The first four sections discuss solid waste products as oxides or modified oxides. The fifth section will compare the properties of borides, carbides, nitrides, and oxides. The comparisons are by no means complete; much work is required to completely and properly compare the different waste compounds. These comparisons do, though, give an indication of the general behavior of each form.

2.5.1 Calcine

Calcines are the simple oxides of waste nuclides formed by the high temperature treatment of nitrate solutions. Four processes have been developed to accomplish this process. They are fluid bed calcines, spray calcines, rotary kiln calcines, and pot calcines. Table 2-21 gives pertinent properties for the calcine products of the four processes. All the calcine products have common disadvantages. They are that the calcine has a low thermal conductivity, has a high leach rate, is a very dispersible powder, and contains residual HNO_3 and other impurities which can be released at elevated temperatures. The processes are described below.

TABLE 2-18. COST PER UNIT AREA OF COST COMPONENTS

Item	Dollars
Structural Materials	24,750/m^2
Process Equipment	61,280/m^2
Bulk Material	59,500/m^2
Site Improvement	30,000,000 (total)

TABLE 2-19. COST FACTOR FOR PARTITIONING SCHEMES

Option	Cost Factor
1	0.593
2	0.784
3	1.0
4	1.446
5	1.168

TABLE 2-20. SOLID WASTE FORMS (WT% WASTE OXIDE)

Calcines	Composites	Glasses
Spray Calcine (100)	Super Calcine (70)	Phosphate Glass (25)
Pot Calcine (90)	Coated Particle (65)	Borosilicate Glass (33)
Fluidized Bed Calcine (100)	Metal Matrix (65)	
Kiln Calcine (100)	Sintered Glass Ceramics (65)	

TABLE 2-21. PROPERTIES OF WASTE CALCINE

	Wt% Fission Oxide (Avg)	Bulk Density g/cc	Thermal Conductivity W/(m°K)	Leach Rate g/cm^2/day at 300°K	Liquidus Temp °K	Corrosion of Containment Vessel Nanometer/Sec	Processing Temp °K
Spray Calcine	100	0.5-1.3	0.2	25-40	1670	0-10	623[a]
Pot Calcine	90	1.1-1.4	0.35-1.0	25-40	1670	0-10	1173[a]
Fluidized Bed Calcine	100	2.0-2.4	0.2-0.3	25-40	1670	0-10	773[a]
Kiln Calcine	100	1.0-1.3	0.2	25-40	1670	0-10	773[a]

(a) Calcine must receive thermal post treatment at 700-900°C to remove residual NO_3^- and H_2O to prevent pressurization during seal encapsulation.

2.5.1.1 Fluidized Bed Calcine[2-53 through 2-55]

During fluidized bed calcining, the nitrate solution is atomized and sprayed onto an agitated granular bed heated to between 500–600 C. The formed calcine particles can range in size up to 1 mm. It is a continuous process easily designed to process 120ℓ HLW/hr, or more. There has been much development work done at ANL,[2-56] IRTS,[2-57] and PNL,[2-58] and the process has been used on both aluminum nitrate and zirconium fluoride-aluminum nitrate waste, and purex-type waste. A disadvantage to the process is its complexity. The advantages are the high processing rate, the ease of scaling up the equipment, its product is easily transported by pneumatic means, and the process is proven. Less than 1 percent of the ruthenium is lost during processing. Ruthenium is of concern because of its vapor transport and subsequent deposition in process equipment where it results in a high background radiation field with high worker exposure. The product can be pressed in pellets improving its thermal properties.

2.5.1.2 Spray Calcine[2-53 through 2-55]

During spray calcining, the nitrate solution is atomized and sprayed into a chamber heated to 700 C where the droplets are flash dried. As they fall, they are calcined to a fine powder which is low in density and thermal conductivity. This continuous process was primarily developed to produce a feed material for glass production and much pilot plant work has been done for this process at PNL[2-59 through 2-61] where a pilot plant has processed up to 200ℓ HLW/hr. Therefore, this process is one that is very feasible. The advantages are that it is easy to produce, it uses common materials, it is a proven technique, and it can process a variety of feed compositions. During the calcining, up to 5 percent of the ruthenium can be volatilized. It would be possible to cold press and sinter or hot press the spray calcine into pellets giving it a higher waste loading capacity and increase its thermal conductivity.

2.5.1.3 Rotary Kiln Calcine[2-53,2-55]

This process is being developed mainly in France,[2-62] where pilot plant operations continuously processed 40ℓ HLW/hr. The process consists of a nearly horizontal heated cylinder rotated at about 30 rpm. The waste is introduced at the elevated end of the calciner and is calcined as it travels down the tube. Loose bars in the furnace break up the formed solids resulting in a finely divided oxide powder which is meant to be a feed to a glass-forming process. The low end of the calciner is operated near 900 C to assure complete calcination. The advantages are that the process is continuous, simple, and the technique is proven. The loss of ruthenium would be intermediate to spray and fluid bed calcines. The product could be pressed into a final product with improved thermal properties.

2.5.1.4 Pot Calcine[2-53 through 2-55]

The process has been used in pilot plants at both ORNL[2-63] and PNL.[2-64] In this process, the nitrate solution is introduced into a stainless steel pot heated to about 900 C. As the pot fills, the flow rate of solution is decreased. The calcine which forms a scale on the sides of the pot contains 90 percent waste oxides and 10 percent additive to reduce volatilization. These pilot plant batch operations have a limit of 12ℓ HLW/hr. Since the canisters are the final disposal containers, they need to be made of a noncorrosive material. A disadvantage of this

process is relatively low processing rate (12ℓ HLW/hr) since it is a batch process. The advantages of the process are: it is a simple, proven process, and it works on a variety of feed compositions. Up to 30 percent of the ruthenium can be volatilized during the process.

2.5.2 Composites

These materials require the basic calcining techniques which are modified to improve the properties of the waste forms. Table 2-22 gives the three composite forms considered and some of their pertinent properties. The processes either add chemicals to reduce volatility, coat the product to reduce its leachability, or place the particles in a material to improve its thermal properties. These waste forms are described in the following subsections.

2.5.2.1 Supercalcine[2-53]

Supercalcine is a term that has been coined at Pennsylvania State University to describe calcines which have had additional chemicals added to the calcine feed which causes the formation of a powder with a thermodynamically stable crystalline structure. This structure holds the volatile nuclides in the waste form to a higher temperature. The supercalcine is more refractory and leach-resistant than normal calcine. The calcining is done using any of the previously discussed calcining processes. PNL has done much work on the use of supercalcines in conjunction with Pennsylvania State University.[2-58] The advantages of supercalcines are: they have better thermal properties and are more leach-resistant than calcine, they can be used at higher temperatures than calcines, they contain the volatile nuclides, and they use proven equipment. The disadvantages are: the thermal conductivity is still low, they do not have high waste loading, the process control is more complex, and the product is in a very dispersible form unless subsequently processed in some manner to achieve a greater bulk density. Very little ruthenium is lost during processing. The supercalcine can be processed into pellets which improve its thermal properties.

2.5.2.2 Coated Particles[2-53]

The particles are made of compressed and sintered supercalcine and are coated with either Al_2O_3 or PyC (pyrolytic carbon).[2-58] The coatings decrease the leach rate of the waste, make the waste more resistant to oxidation, and improve the thermal properties of the waste. The supercalcine is pressed into pellets larger than 1 mm, then these pellets are coated. The pellets then can be packaged for storage. The disadvantages of this waste form are that it requires very complex processing, has a low waste loading, is in a dispersible form, and is not a completely proven or demonstrative technology. The advantages are the product has good thermal conductivity (not if loose pellets), good resistance to leaching, and good resistance to oxidation.

2.5.2.3 Metal Matrix[2-53,2-58]

The waste form is produced by placing the waste pellets in a container; then the metal is added as either a liquid or a powder, and the container is then sealed and sintered. The metal used for matrix material can be most anything if it is compatible with the waste form and container. Some of the metals considered are lead, aluminum and copper. The disadvantages of

TABLE 2-22. MINIMAL ADDITIVE CASES

	Wt% Fission Oxide (Avg)	Bulk Density g/cc	Thermal Conductivity W/(m°K)	Leach Rate $g/cm^2/day$ at 300°K	Liquidus Temp °K	Corrosion of Containment Vessel Nanometer/Sec	Processing Temp °K
Super Calcine	70	4[a]	0.6[a]	10^{-5}-10^{-4}	1670	0-10	1170-1370
Coated Particles	65	3.7	17	10^{-5}-10^{-4}	1670	0-10	1670
Metal Matrix	65	3.4	5-35	10^{-4}-10^{-3}	600	0-10	1470

(a) Values for hot pressed calcine.

metal matrices are: complex processing, low waste loading, low melting point, use of unproven technology, and the waste form is heavy. The advantages are: a thermal, conductive, leach-resistant product and a form that is less likely to disperse waste.

2.5.3 Glasses

These forms are the most promising for the terrestrial disposal of HLW. Their physical properties are such that they afford excellent isolation of the HLW from man and Table 2-23 shows the properties of these forms. The two glass types (borosilicate and phosphate) are nearly identical except for the different additives, but these different additives cause different properties to be exhibited. These forms are briefly described in the following subsections.

2.5.3.1 Borosilicate Glass[2-53]

This glass is produced by mixing waste calcine and glass forming constituents together and melting the mixture. The molten mixture is then placed in containers and allowed to cool. The glass forms a solid mass which reduces the leachability of hazardous nuclides from the mass. The thermal properties of the glass are better than calcine, but not as good as the metal matrix. The borosilicate glasses are thermally more stable than phosphate glasses. The disadvantages of the borosilicate glasses are: low waste loading and moderate thermal properties. The advantages are: the form is not easily dispersed, the product is leach resistant, and the technology is available.

2.5.3.2 Phosphate Glass[2-53 through 2-55]

This type of glass is produced by mixing liquid waste with orthophosphoric acid. The mixture is concentrated to a viscous slurry and is transferred to a melter for converstion to molten glass at 1373 K. The product is then poured into containers to cool into a solid monolith. The glass is more corrosive than the borosilicate glass, although the thermal properties are about the same. The disadvantages are: low waste loading and moderate thermal properties. The advantages are: the glass is not easily dispersed, it is leach resistant, and the technology is available.

2.5.4 Cost of Waste Solidification

A detailed economic breakdown of the solidification of waste has not been made recently, although the capital cost was broken into various components:[2-65] the components are facilities, cell structures, and pieces of equipment. From these estimates it is possible to estimate a cost factor relative to the different processes. The difference in capital cost for the different types of calcine production, except the pot, are very similar and are assumed to be equal. The base case is glass formation which is given a cost factor of 1.0. It is assumed the cost of either type of glass formations is equal. Table 2-24 gives a comparison between several of the solid forms.

The cost of producing coated pellets or metal matrix has not been determined. The cost of the pellets will be greater than the calcine. Therefore, the cost factor could be assumed to be greater than 0.7. The cost of the metal matrix will be greater than the cost of the coated pellets, but the exact cost is not known.

TABLE 2-23. PROPERTIES OF MIXTURES

	Wt% Fission Oxide, (avg)	Bulk Density, g/cc	Thermal Conductivity, W/(m°K)	Leach Rate, g/cm^2 day at 300K	Liquidus Temp, °K	Corrosion of Containment Vessel Nonometer/Sec	Processing Temp, °K
Borosilicate Glass	33	3.0-3.6	0.9-1.3	10^{-7} to 10^{-4}	820-1020	0-10	1673
Phosphate Glass	25	2.7-3.0	0.8-1.3	10^{-7} to 10^{-3}	820-1020	0-10	1373

TABLE 2-24. SOLIDIFICATION COST FACTOR

Process	Factor
Calcine (Spray, Fluid, & Supercalcine)	0.7
Pot	0.66
Glass	1.0

A recent report that examined the overall cost of waste solidification[2-66] at a 1500 MT/yr plant gave a reasonable capital cost for a glass solidification process as between $40–80 million.

2.5.5 Alternate Waste Compounds

The waste product oxides tend to have a low density and thermal conductivity which limit the amount and geometries that can be used in designing the containment vessels for the waste. The following subsections discuss the possibility of using other compounds as basic waste forms. The items that will be compared are their thermal conductivity, melting points, their atmospheric stability, compatibility with containment vessels, density and densification, leachability, and their preparation techniques. The comparisons are very general. Only detailed work can determine if they are valid.

2.5.5.1 Thermal Conductivity

To load the maximum amount of waste into a container, its decay heat must be transferred to the environment as efficiently as possible, and the temperature of the waste form should not exceed its processing temperature. Therefore, high thermal conductivity and/or melting point is desired for the waste form. Table 2-25 presents the thermal conductivity for various materials and the fraction of the nulcide present in waste, but the thermal conductivity data are sparse. The data tends to point out that borides have generally higher thermal conductivities than oxides. The conclusions have been made concerning the overall thermal conductivity of the compound in question.[2-67] It has been concluded that the thermal conductivity of the compunds at high temperatures (1100 C) are ranked B>C>N>O.[2-67] The oxides tend to be the poorest in terms of thermal conductivity.

2.5.5.2 Melting Point

The data on a compound's melting point is more available than the data on thermal conductivity, but it is still lacking for some elements. The melting points for some of the materials are shown in Table 2-26. The data show that basically the melting points of the materials are very close. There are some compounds, i.e., Cs_2O, TeO, PdO, CsN, which have low melting points, but their behavior in the mix is not known. They may form intermolecular structures which could affect the melting point of the total mix, but this is not known; therefore, additional studies must be conducted to determine if this is possible.

2.5.5.3 Stability in Atmosphere

Of the four compound types, the oxides tend to be the most stable in air, the borides, carbides, and nitrides tend to oxidize readily. The oxidation rate is enchanced if water vapor is present in the system. The borides are the next most resistant, with zirconium and molybdenum boride being the most resistant; Table 2-27 gives some information on the stability to oxidizing atmosphere. Since the oxides tend to hydrolyze and the borides will first form oxides which will form hydroxides, the stability of the waste form may be no better than the oxide form for any of the alternate forms. The carbides, borides, and nitrides are stable if used in reducing or neutral atmosphere, but if any accident occurred, the specialized waste forms could revert to the common oxide form. It cannot be guaranteed that all oxidizing material will be removed from the system; therefore, the use of alternate forms may be to no avail. The order of resistance to oxidation is O>B>C>N.

TABLE 2-25. THERMAL CONDUCTIVITY, $\frac{W}{m^{o}K}$ AT 1373 K

	Oxide	Boride	Carbide	Nitride	Weight Fraction Solid Waste for Option 3
Sr	249.2	45.0			.0255
Y	8.65	29.2			.0134
Zr	2.0	60.5	38.0	24.2	.106
Mo			40.0	17.3	.103
Tc					.0246
Ru					.0673
Rh					.0113
Pd					.0403
Te		(a)			.0167
Cs		(a)			.0789
Ba	399.7	46.9			.0412
La		47.7			.0371
Ce	10.4	20.0			.0784
Pr		41.0			.0356
Nd		47.2			.1143
Sm	2.1	13.8			.0239
U	2.5	5.0	34.6	20.0	.139
Np					.0139
Pu			12.6	15.0	.0013
Al_2O_3 (Particle Coating)	32.9(b)				
Total Fraction					0.971

(a) Compounds not formed.
(b) Single crystal value.

TABLE 2-26. MELTING POINT C^{o}

	Oxide	Boride	Carbide	Nitride
Sr	2460	2236	1700	1030
Y	2417	2300	2300	2670
Zr	2715	3265	3500	2980
Mo	1927	2100	2500	900
Tc	2127			
Ru	1127			
Rh	1127			
Pd	877			
Te	747	(a)		
Cs	490	(a)		310
Ba	1923	2270	1760	2220
La	2315	2210	1800	
Ce	2142	2190	2190	
Pr	2200		2200	
Nd	2315	2540	2000	
Sm	2320	2540	2200	
U	2603	2365	2350	2630
Np	2327			
Pu	2240		1654	2750
Al_2O_3	2050			

(a) Compounds not formed.

TABLE 2-27. OXIDATION REACTION TEMPERATURES

	Boride	Carbide	Nitride	Oxide
Zr	982°C	426°C	537°C	Stable
Ba, Sr	537°C	27°C H_2O	27°C H_2O	Hydrolyze in Moist Air
Mo	982°C	815°C	27°C	--
RE (Rare Earths)	Less Than 982°C	27°C H_2O	27°C H_2O	Hydrolyze in Moist Air
U	982°C	∿27°C H_2O	500°C H_2O	Go to U_3O_8

2.5.5.4 Compatibility with Containment Vessel

To be useful as a waste form, the form must be compatible with its containing structure, materials which are normally stainless steels or titanium alloys. The oxides tend to be fairly inert toward these materials. There are indications the UC and other carbides react with many metals including stainless steel at about 1000 C.[2-68,2-73] Here again, finding a material that can contain the boride waste form may be a problem, one with a costly answer. The metals which seem to be compatible with borides, carbides, nitrides, and oxides are copper and silver while Nb is compatible with borides. A thin layer of copper inside a container of another metal will contain the materials if the melting point of copper is not reached. If the container keeps its integrity, the waste will be contained economically.

2.5.5.5 Density and Densification

The density for the various compounds are shown in Table 2-28. There are gaps present in the table, but it can be seen that the theoretical densities do vary significantly between compound types. For the rare earths and alkali metals, the oxides have the higher density. The nitrides have the next highest density with the carbides next and the borides with the lowest. The actinides show the nitride with the highest, the carbides next, the borides next to the lowest, with the oxides at the bottom of the list. The percentage of the weight actually caused by the radioactive nuclide is shown in Table 2-29. This was calculated by looking at the molecular weight of the compounds and finding what percentage was due to the waste nuclide only. For the compounds shown, the average waste nuclide weight for oxides is 85 percent, for the borides is 74 percent, for the carbides is 89 percent, and for the nitrides is 90 percent.

For space disposal, it is desirable to have the maximum density possible. The values shown on Table 2-28 are theoretical values. To reach these values, the product of the various processes needs to be densified. The extent of densification can depend on the physical properties of the ceramics, however, very little work has been done on densifying the mixed ceramic powders. It is not possible to estimate the approach to theoretical density that will be achieved with the mixture. There has been some work done on compressing various compounds using high heat and great pressure: uranium oxides have been pressed up to 99.9 percent of theoretical density,[2-76] borides have been compressed to over 97 percent of the theoretical,[2-78,2-79] and uranium carbide and nitride have both been pressed up to over 98 percent of the theoretical.[2-78] Some of the compounds in a mixture would not be stable under the conditions needed to obtain these levels of compaction. Another consideration is that these values were for small pellets. If these pellets were placed directly into a container, the actual density of the material in the container will decrease due to incomplete packing. The thermal properties of the waste would also decrease. To eliminate as much as possible this problem, the waste would have to be compacted directly in the container to get the maximum possible density. This technique is not presently feasible.

To estimate the amount of waste that can be carried by a unit of volume, the density of each nuclide on Table 2-28 was multiplied by the weight percentage on Table 2-29 and by the weight percentage present in the waste for the nuclide as found on Table 2-25. By normalizing to 1.0 the results for each compound, it was found that the oxide form would include 6.11 g waste/cc, 6.00 g waste/cc for the borides, 7.52 g waste/cc for the carbides, and 8.42 g waste/cc waste. The carbide has the highest waste loading, next is the oxide, and last is the boride. The rare earth borides have a low waste loading; which causes the low overall boride waste loading.

TABLE 2-28. THEORETICAL DENSITY, g/cc

	Oxide	Boride	Carbide	Nitride
Sr	4.7	3.44	3.04	
Y	5.03	3.7	4.53	5.9
Zr	6.1	6.09	6.56	7.35
Mo	4.1	9.31	9.12	9.18
Tc	6.9	--	11.5	--
Ru	6.97	--	--	--
Rh	8.2	--	--	--
Pd	8.7	--	--	--
Te	5.67	--	--	--
Cs	4.25	--	--	--
Ba	5.72	4.32	3.57	--
La	6.51	4.72	6.08	6.85
Ce	7.2	4.82	6.97	8.09
Pr	10.9	4.86	6.62	7.49
Nd	7.24	4.95	6.9	7.69
Sn	7.62	5.07	8.14	8.5
U	10.96	12.73	13.63	14.32
Np	11.11	--	--	--
Pu	11.46	14.10	14.0	14.25

TABLE 2-29. PERCENT OF WEIGHT DUE TO WASTE NUCLIDE

Sr	SrO .85	SrB_6 .57	SrC_2 .78	
Y	Y_2O_3 .79	YB_6 .58	YC_2 .79	YN .86
Zr	ZrO_2 .74	ZrB_2 .81	ZrC .88	ZrN .87
Mo	Mo_2O .92	Mo_2B .95	Mo_2C .94	MoN .87
Tc	--	--	--	--
Ru	--	--	--	--
Rh	--	--	--	--
Pd	--	--	--	--
Te	--	--	--	--
Cs	--	--	--	--
Ba	BaO .90	BaB_6 .68	BaC_2 .85	--
La	La_2O_3 .85	LaB_6 .68	La_2C_3 .89	LaN .91
Ce	CeO_2 .81	CeB_6 .68	Ce_2C_3 .89	CeN .91
Pr	Pr_2O_3 .81	PrB_6 .68	Pr_2C_3 .89	PrN .91
Nd	Nd_2O_3 .86	NdB_6 .69	Nd_2C_3 .89	NdN .91
Sm	Sm_2O_3 .86	SmB_6 .70	Sm_3C .97	SmN .91
U	UO_2 .88	UB_2 .92	UC .95	UN .94
Np	--	--	--	--
Pu	PuO_2 .88	PuB_2 .92	PuC .95	PuN .95

Table 2-30 is useful in determining the volume of waste to be disposed in space. The table was derived using results found in Section 2.5.5.5, that is, that the oxides contain 6.11 g waste/cc waste form, the borides contain 6.00 g waste/cc waste form, the carbides contain 7.52 g waste/cc waste form, and the nitrides contain 8.42 g waste/cc waste form at theoretical density. An assumed level of compaction of 56% for cold pressed material and greater than 95% for hot pressed is made for the basic compounds. The amount of waste oxide in each of the modified oxide forms is found on Table 2-20. To determine the volume of waste to be disposed of, the mass of waste requiring disposal is determined by using the procedure outlined in the preceding paragraph. This mass is multiplied by the corresponding waste form factor from Table 2-30 to get an estimate of the volume of waste to be disposed using average values. A more exact value could be determined with detailed work.

2.5.5.6 Leachability

Data on the leachability of the various waste compounds is not available. The leach rates for oxides are high, as can be seen on Table 2-21. The leach rate of other waste forms can be assumed to be equal to or greater than this due to their rapid oxidation by the air and water. Therefore, for leach resistance, none of the compounds are outstanding. Studies should be performed to verify this assumption.

2.5.5.7 Methods of Formation

The methods for forming the different compounds vary greatly from compound to compound. The simplest forms produced are the oxides which are formed by calcining nitrate solution. The solution is atomized and sprayed into a heated chamber where the nitrate forms of the nuclides are converted to the oxide form at a temperature of about 700 C. A constant supply of air provides oxygen for the reaction.[2-59] Some of the fission products (ruthenium and cesium) are partially vaporized off.

The formation of borides is more complicated than oxide production. There are three methods which could adapt themselves to large-scale production of borides. The three methods all involve the prior production of the oxides of the nuclides.[2-70 through 2-72] The first method is an electrolysis method which is conducted at around 1000 C. Boric oxide and the nuclide oxides are dissolved in a molten mixture of alkali-alkaline earth halides. The current passing through the molten mass reduces the oxides to borides which deposit at the cathode. The current efficiency of the process is very poor (around 5.7%). The process is effective for the formation of the barium, tin, molybdenum, and rare earth borides. The second method operates at 1500 C and reduces the oxide with carbon in the presence of B_2O_3. The product form tends to be contaminated with carbon. The process produces borides of molybdenum, zirconium, and the rare earth. The third method is the borocarbide method. In this process, boron carbide (B_4C) and the oxides are reacted at about 1600 C. This process is good for the production of hexa-, tetra-, and di-borides of the nuclides. The overall technology for the formation of borides is known, but if they will work on nuclear waste is not known.

There are two popular methods for the production of carbides.[2-73] One starts with the elemental metal and one uses the oxide. The processes are the same except for operating temperature and reactants. The process which uses the metals as a starting material reacts carbon with the metal at around 1600 C. In the second case, the oxide is mixed with carbon and reacted at around 2000 C in an arc furnace. The products from both processes are fairly pure due to the lack of contaminates introduced during processing. Both processes work well on rare earths and transition metals.

TABLE 2-30. MASS TO VOLUME MULTIPLICATION FACTOR(a)

Solid Waste Form	Specific Volume
Nitride	0.21
Carbide	0.24
Oxide	0.29
Boride	0.3
Supercalcine	0.36
Coated Pellet	0.42
Metal Matrix	0.45
Borosilicate Glass	0.84

(a) $\frac{\text{cubic meters}}{\text{MT}}$.

The nitrides are formed by preparing the oxides.[2-74] The first of two possible methods reacts the oxide with carbon in a nitrogen atmosphere at 1000 C. The product is impure, containing carbides of some of the elements. The second method mixes the oxide and carbide forms of the element and reaction in a nitrogen atmosphere at around 1800 C. There is a possibility of having impure products from this process which works well on transition metals and rare earths.

The basic drawback with the formation of the compounds other than the oxide is that it is necessary to first form oxide which adds great expense to the overall waste management. Additional problems relate to the high temperature processing required which leads to uncontrolled vaporization losses, and to the impurities introduced which might affect chemical reactivity with containers, leachability, and melting point. There has been no attempt to estimate the cost of producing the alternate waste compounds.

2.5.5.8 Summary of Alternative Waste Forms

It is obvious that in theory there are possible waste forms other than the calcine and its various modifications which appear to have quite attractive properties from the standpoint of disposal in space. The desired properties include high density, high thermal conductivity, chemical stability, economy of preparation, and ease of densification. While it is not apparent that any single class of compounds exhibit all of these attributes, it is probable that one may have a better combination than does the calcine. The greatest uncertainty relates to the extremely complex chemistry of the high-level waste which contains a very large number of elemental components, some of which may not form the desired compound, or which may have undesirable characteristics if they do. While it is fairly straightforward to hypothesize about such matters, extensive experience exists which would recommend against any approach other than a comprehensive experimental program to resolve these matters.

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3.0 CONTAINERIZATION

After solidification of the waste it is necessary to enclose it in a container that will serve as its final enclosure for disposal in space. In addition, this container will serve as part of the packaging for the transportation of the waste to the launch site. However, due to the regulations governing such ground transportation, additional protection will be required during that phase of the operation. The packaging for the solidified waste will be highly dependent upon the waste form, the life time, destination, disposal method, and the safety and environmental aspects of the transportation modes from origin to destination. Thus, a definition of the packaging design was initiated by a parametric study. This study considered such factors as composition, physical and thermal properties, heat generation, compatibility with structural materials, shielding requirements, and criticality control requirements of the waste. Design parameters were defined by normal and potential accident scenarios of pre-launch, launch, and orbital operations. During launch and orbital operations, the vast range of external heat sinks and sources and the high acceleration and possible impact loads defined the thermal and structural criteria for the packaging.

3.1 Parametric Packaging Study

Evaluations of packaging involve considerations of waste forms, a canister design, thermal considerations, shielding, modes of transportation, and handling up to the time of launch. Each is treated in the following portions of this section. To show the overall relationship of each of the components or factors in the system, a possible concept for the overall packaging and ground transportation system is shown in Figure 3-1. This is not intended to show a recommended design but to show the general relation among the subsystems and components discussed in detail in the following sections.

3.1.1 Waste Forms

The subject is treated in detail in Section 2 of this report. For purposes of this study the high level waste is assumed to be a high density (4-6 g/cc) oxide material with all volatile fission products removed which is essentially state of the art. All actinides are retained with the exception of uranium and plutonium which have been recovered to 99.5 percent. Thus only 0.5 percent of each is in the waste. Other waste form schemes are possible and will be required to optimize the space disposal concept; these are described in detail elsewhere.

3.1.2 Canister Configuration Evaluation

3.1.2.1 Tentative Design Criteria for Canister

The design criteria for the canister are based on the following:

(1) Maximum payload per unit weight

(2) Waste density of 4 g/cc with consolidation to 6 g/cc

(3) Nominal capacity of 1 cubic meter of HLW

(4) Maximum temperature of 1000 C for HLW (or not to exceed the maximum processing temperature)

(5) Passive cooling after Earth orbit

(6) Ability to survive reentry into the atmosphere with the cocoon

(7) Ability to survive ocean impact

(8) All protective packaging is separate

(9) Shipping cask satisfies NRC/DOT requirements and regulations

(10) Compatibility with all phases of the waste stream handling from the processing facility to ejection into space

(11) Minimum number of internal cooling fins

(12) Total radiation dose (gamma plus neutron) at 1 m from canister surface to be within 2 R/hr.

3.1.2.2 Conceptual Design

The canister configuration considered here consists of a thin-walled cylinder about 1 m in diameter by 1 m long. The cylinder walls are 2-1/2 cm thick and the ends are 5 cm thick. The lid is sealed by welding. The canister is niobium to give the required elevated temperature structural properties and thermal properties. Materials selection is discussed in later sections of this report.

The radiation shielding, as concepted here, consists of a thin-walled cylinder and end plates of an efficient gamma shielding material, depleted uranium, which completely encloses the canister. Inasmuch as this material, as well as some alternates, is not a structural material and is subject to oxidation, the shielding material must be enclosed to exclude oxygen and moisture. This enclosure should also offer impact protection to the shield. For purposes of weight efficiency and to limit the number of material interfaces which act as thermal barriers, the concept considers that the uranium is sandwiched between two walls of stainless steel. The inner wall is relatively thin, nominally 0.5 cm, and serves as a cladding to prevent oxidation. The outer wall must be thicker to offer structural properties, and for this concept, is assumed to be the stainless steel cylindrical wall of the cocoon. Thus this part of the cocoon would be integral with the canister-shielding package and will remain with the package from the Reprocessor to the time of withdrawing the canister from the Shuttle. The other cocoon components, the nose and tail sections, will be attached to the package at the launch site.

On the basis of the relative fissile content of the various disposed waste mixes, all appear to have no potential for criticality problems in this configuration, with the exception of Mix No. 2. In Mixes Nos. 1, 3, 4 and 5, the fissile content is less than that in natural uranium, whereas the removal of the uranium diluent in Mix No. 2 gives a significantly higher fissile content.

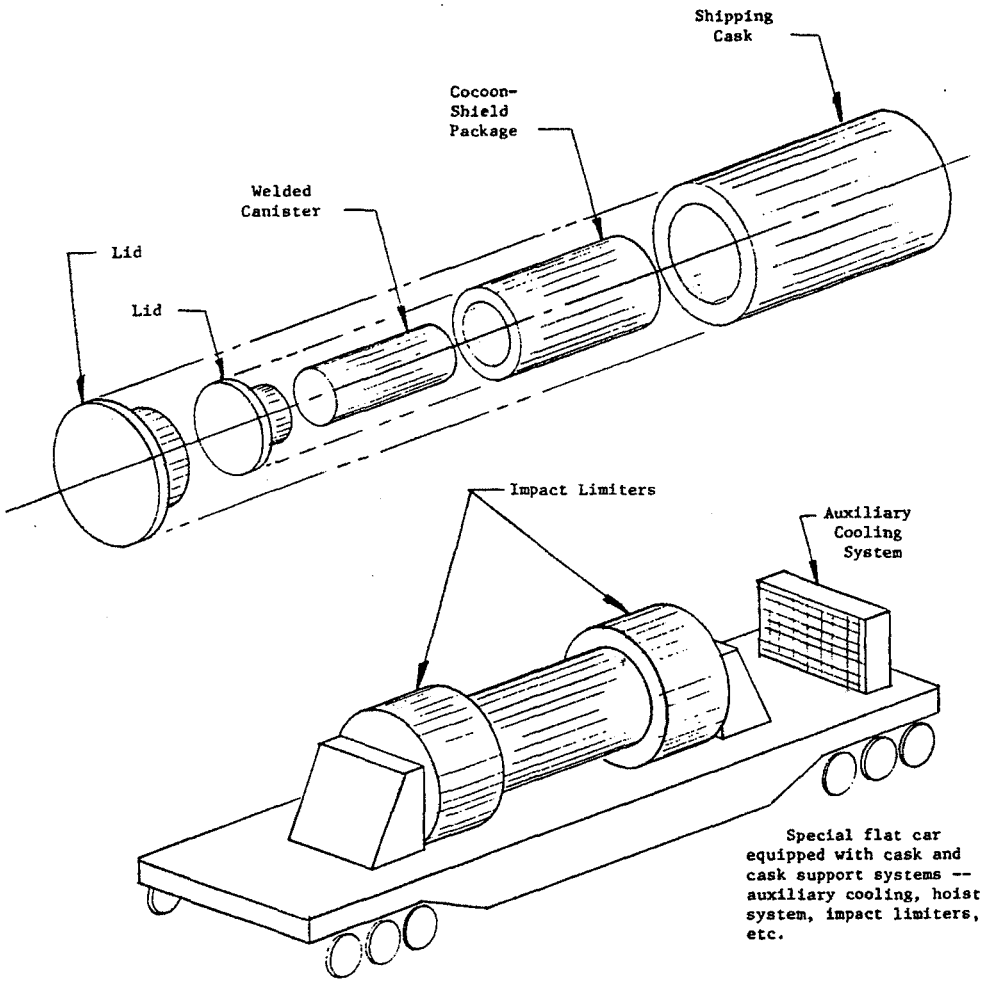

FIGURE 3-1. CONCEPT FOR OVERALL CONTAINER SYSTEM

3.1.3 Shield Requirements for the High-Level Waste Container

Calculations were performed to assess the neutron and gamma shielding requirements for the conceptual design of a HLW container. The ORIGEN[3-1] code was used to estimate the radiation source term for the analyses. ORIGEN predicts the generation of fission products and the transmutation of isotopes through neutron reactions and decay. The design basis fuel was chosen as pressurized water reactor fuel, irradiated for 3 years to a burnup of 33,000 MWD/MT, reprocessed 0.5 year after discharge and decayed for 10 years after reprocessing; 0.5% of the uranium and plutonium remained after reprocessing. The gamma source strength is shown in Table 3-1 as a function of energy. The energy group structure is provided by the ORIGEN code. The neutron source strength obtained is 3.0×10^8 n/sec per metric tonne of uranium charged to the reactor (MT of uranium). The neutron source is composed of neutrons from spontaneous fission and from alpha reactions with oxygen. In the analyses the spectrum was taken as the ^{235}U fission spectrum.

The QAD[3-2] code was used to analyze the adequacy of gamma shielding. The QAD approach is based upon an estimation of the uncollided flux at the dose point modified by a buildup factor for each energy group. QAD has a flexible three-dimensional geometry capability. Self-shielding within the source (HLW) region is automatically accounted for by the method. The buildup factors in niobium and stainless steel were represented by the iron dose buildup factor and in uranium by the lead dose buildup factor.

Neutron calculations were performed with the ANISN[3-3] code. ANISN is a one-dimensional discrete ordinates solution to the transport equation. In the analyses the S_8P_3 approximation was used with the 22 neutron group cross sections from the DLC-23/CASK[3-4] library. Calculations were performed in cylindrical geometry. Because of the one-dimensional geometry limitation, ANISN can only be used to predict the dose at the surface of the container. Dose values at distances from the container were obtained using the neutron capability of the QAD code. The ratio of the QAD dose at some distance from the container to the QAD surface dose was multiplied times the ANISN surface dose to estimate the dose at that distance.

In Table 3-2 the configuration is shown for the conceptual design obtained from the shield design exercise. The waste region was taken as 58.5 cm in radius with a length of 117 cm containing 5.0 MT of waste at 4.0 g/cc. The gaps between the shield regions were not modelled in the analyses. In the neutron calculations the niobium was approximated as stainless steel. In both the neutron and gamma calculations the uranium shield was artificially placed at the outside region of the shield for convenience. The goal for the design was a maximum dose of 2 R/hr at 1 meter from the surface. The results of analyses showed, however, that the neutron dose could be reduced to approximately this level without a special neutron shield of hydrogenous material. Due to moderation of neutrons by O_2 it was, therefore, recommended not to include a neutron shield in the design, but rather to assume that portable neutron shielding would be used as required to protect personnel. The gamma shield thickness was varied to achieve a gamma dose of 0.5 R/hr. This value was chosen to leave margin for uncertainties in the analysis and for a contribution from neutrons. The dose rates obtained from the analyses are shown in Table 3-3.

Gamma calculations obtained for different source densities within the same container inner diameter indicated that the dose was nearly independent of density. The increase in self-absorption in the source region was found to balance the increase in source strength.

TABLE 3-1. PHOTON SOURCE STRENGTH

$\bar{E}$ (MeV)	Source Photons/Sec, MTU
0.30	1.67×10^{14}
0.63	3.87×10^{15}
1.10	1.37×10^{14}
1.55	9.16×10^{12}
1.99	9.12×10^{10}
2.38	2.53×10^{10}
2.75	2.00×10^{9}
3.25	7.28×10^{7}
3.70	6.34×10^{6}
4.22	4.00×10^{6}
4.70	1.89×10^{6}
5.25	1.19×10^{6}

TABLE 3-2. CONCEPTUAL CONTAINER SHIELD

Shield Material	Inner Radius (Cm)	Thickness (Cm)
Niobium	58.5	2.5
Uranium	61.5	5.6
Steel	67.6	3.0

TABLE 3-3. CONTAINER DOSE RATES

Radiation	Surface Dose (R/hr)	One-Meter Dose (R/hr)
Neutron	9.5	2.5
Gamma	1.5	0.52

In the neighborhood of the design values used for the shield, a change in the dose can be related to changes in the uranium thickness according to the approximate relationships

$$\frac{\delta D_n}{D_n} = e^{-0.40\delta x}$$

$$\frac{\delta D\Upsilon}{D\Upsilon} = e^{-\delta x}(1+0.55\delta x)$$

where D_n = neutron dose
$D\Upsilon$ = gamma dose
δx = change in uranium thickness in cm.

QAD calculations performed with an 18-group energy structure rather than the ORIGEN 12-group structure indicated an uncertainty of approximately 100 percent in the gamma dose associated with group structure. The more conservative values obtained with the 18-group structure are reported. A more detailed evaluation would be required, however, to narrow this uncertainty. A similar uncertainty exists in the buildup factors employed.

A considerable uncertainty exists in the proper neutron source strength to be used in the analyses. The neutron source is more sensitive to the assumed fuel cycle parameters than the gamma source. In particular, the neutron source would be increased significantly for plutonium recycle. The uncertainty in the computational techniques for the neutron calculations are also believed to be approximately 100 percent.

3.1.4 Preliminary Evaluation of Thermal Problems

Thermal analyses were performed for the high level waste container subjected to several environments. The following are the conditions that were analyzed, assuming Mix No. 3 waste:

(1) Waste canister in deep space (steady-state)

(2) Waste canister from time of fabrication until enclosed in shielding (transient)

(3) Waste canister in shield (steady-state)

(4) Waste canister in transfer mode between various "container" stages: shipping cask, storage at launch site, in the Space Shuttle Orbiter, and deep space transfer (transient).

The purpose of this preliminary analysis was to determine the thermal distribution within the critical regions of the various structures as well as to determine the feasibility of the design, within tolerable limits. Due to the many different problems involved, the thermal analyses were performed using the TRUMP[3-5] computer program, a proven heat-transfer code for both transient and steady-state analyses.

3.1.4.1 Model Description

Since the waste canister geometry is essentially axisymmetric, this profile was chosen to model the temperature behavior with TRUMP. In the computer model, the upper and lower surfaces are planes of symmetry (adiabatic boundaries). End effects were neglected, hence the design is conservative.

Earlier studies by NASA[3-6], and others confirm that a homogeneous mixture of standard calcine waste in sizes approaching 1 meter in diameter generate excessive centerline temperatures, in terms of inducing thermal instability in the waste. In order to limit the maximum temperature, the use of internal fins has been suggested as a feasible alternative. Although there are several methods of using fins for internal cooling (such as radial fins, etc.), the planar design was chosen as representative, simplistic for modeling purposes, and most compatible with easy loading of the waste form. By planar is meant that the waste canisters are filled with alternate layers of calcine waste and thin fin "plates". As discussed previously, the canister configuration is a circular cylinder with diameter equal to the length. This configuration approximates the efficient surface-to-volume ratio of a sphere. In addition, if the volume of waste per canister is to be approximately one cubic meter, the resulting length and diameter are 1.08 meters.

The canister configuration consists of the calcined waste and fins in alternate layers, surrounded by an outer wall. As discussed in Section 3.1.5, the materials considered for these structures are pyrolytic graphite and niobium, respectively. It should be reemphasized that this type of graphite is attractive because of its excellent thermal conductivity. However, it is also anisotropic, with the conductivity reduced by over a factor of 300 in the perpendicular direction. Since contact is much more easily achieved in the axial direction, and also because it is the shorter distance between adjacent fins, the less conductive plane was chosen to coincide with the canister axis. Since the niobium thickness is not an important factor for the thermal analyses, a representative thickness of about 6.35 mm was chosen. The actual thickness of the outer canister wall will be determined by structural and shielding analyses.

3.1.4.2 Waste Canister in Deep Space

The canister is planned to exist in this mode of operation for most of its lifetime; therefore it was decided to base the thermal design of the canister on this condition, assuming that the allowable maximum centerline temperature is the same for all conditions. Consequently, the outer surface will radiate the decay heat to space at absolute zero. No incident solar radiation, or any other external heat source was taken into account for this calculation. Table 3-4 lists the physical properties used in the computer solution. Perfect contact was assumed to exist at all material interfaces. In more refined calculations the niobium-to-graphite gap must include a thermal resistance term. The results indicate that the maximum waste temperature will be about 1000 C if the waste segment axial dimension is 0.250 m and the pyrolytic graphite is 0.04 m thick. The maximum graphite fin temperature is 403 C, and the niobium maximum is 390 C. For a waste volume of about 0.92 m^3 the canister will require 4 equally spaced graphite fins. The corresponding canister length (adjusted for internal fins) is 1.16 m. (See Figure 3-2.) Obviously, the analytical model applies only to internal regions of the waste canister. Consequently, due to end effects, the upper and lower waste regions could be made thicker. For the design in Figure 3-2, the waste volume is 0.92 m^3. By adding 0.045 m of waste to each end, the volume becomes 1.0 m^3, and will probably not exceed the 1000 C temperature limit of the high-level waste.

TABLE 3-4. INPUT PROPERTIES OF WASTE CANISTER DESIGN IN DEEP SPACE

Property	Temperature (C)	High-Level Waste	Graphite Fin	Canister Wall (niobium)
Density (kg/m^3)	all	4000.0	2250.0	8570.0
Heat capacity ($\frac{W-HR}{kg-C}$)	all	0.2	0.2	0.08
Conductivity ($\frac{W}{m-C}$)	0	0.3	2130.0*	47.6
	27	↓	1960.0	
	527		670.0	
	1000			63.2
	2000		260.0	
Heat generation (kW/m^3)	-	23.0	-	-
Emissivity	all	-	-	0.7

* Preferred orientation = radial direction. Values in axial direction are approximately a factor of 330 smaller.

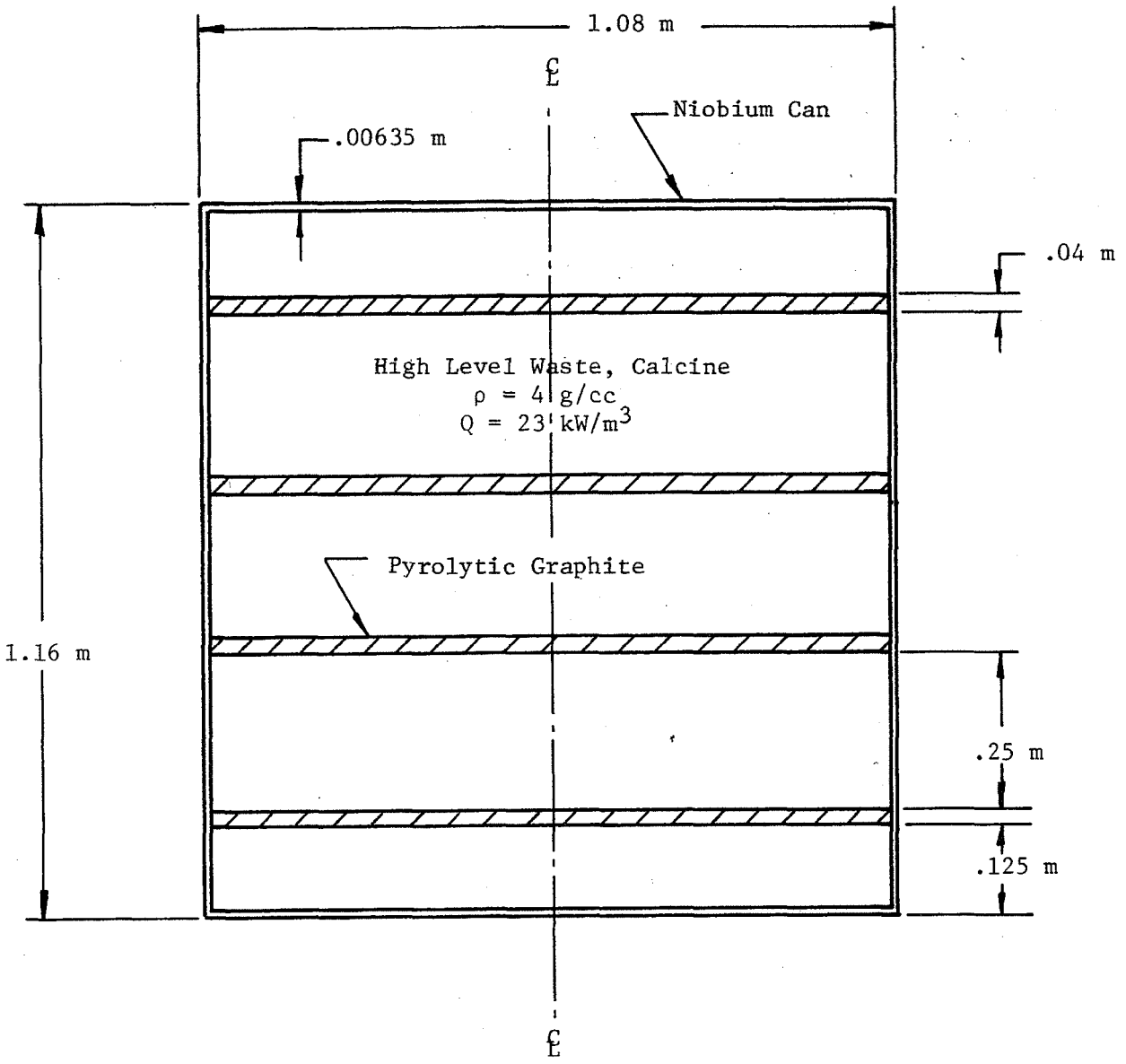

FIGURE 3-2. HIGH LEVEL WASTE CANISTER

Design Basis = Steady-state operation in deep space.

3.1.4.3 Effect of Parameter Variation

Since there are many alternatives to this particular solution, the following is a disucssion of the potential effects of the variation of individual parameters of the waste canister design.

3.1.4.3.1 Density

The present waste calcine methods are expected to achieve solidification densities in the range of 2-2.3 g/cc[3-7] (2000-2300 kg/m^3). The effect of increasing density is to permit more waste to be transported in a smaller volume, with the added advantage of lower internal temperatures due to increased thermal conductivity and smaller radius. For purposes of this study, therefore, it is advantageous to achieve as high a particle density as possible. The theoretical maximum calcine waste density is about 6 g/cc. As a practical upper limit, a value of 4.0 g/cc was assumed to be achievable.

Values of density for the other materials used do not vary significantly as to alter results.

3.1.4.3.2 Heat Capacity

The basis for the HLW value chosen is the isotopic composition of the waste product. A weighted average of known component heat capacities yielded a value of 0.2 W-hr/kg-C. No range of values has been determined for the particular waste composition given; however, little significant variations would be expected due to the similar properties of the various components.

3.1.4.3.3 Conductivity

The range of expected thermal conductivity values for calcine waste products is about 0.17-0.29[3-7] W/m-C, and 0.20-0.30[3-8] W/m-C, for a density of about 2 g/cc. A value of 0.3 W/m-C was assumed for the thermal analysis. Obviously, the higher the conductivity, the lower the centerline temperature. However, no data are available that indicate waste conductivity will be much higher than what has been assumed, although, with the use of internal cooling fins, the effective waste conductivity can be enhanced. As pointed out previously, pyrolytic graphite fins were incorporated into the canister design because of their high conductivity. In order to account for the anisotropic nature of this material, the conductivity in the axial canister direction was assumed to be about 330 times smaller than in the radial direction.[3-9]

3.1.4.3.4 Emissivity

The niobium canister wall is assumed to have a high-emissivity coating on its outer surface. Considering the effects of fabrication, this surface will not be polished, rather it will probably be treated. An average total emittance of 0.7 has been reported for niobium in an oxidized state, at temperatures up to 1000 C.[3-10] It may be possible to achieve values up to 0.85-0.90; however, this will depend on surface coating developments.

3.1.4.3.5 Geometry

It has been the primary basis for this analysis that the "optimum" waste canister design must be a compact cylinder (L/D $\simeq$ 1.0), with a minimum number of internal fins. These two major constraints are conflicting in that individually they would dictate vastly different designs. That is, a "squat" cylinder will require numerous fins to reduce centerline temperatures, while conversely, a minimum number of fins would be required for a long, thin cylinder. It has been assumed, for this analysis, that the minimization of fins requirement is secondary in importance to the payload launch limitations. Consequently, for about a cubic meter volume of waste, and L/D = 1.0, at least four graphite "plates" of 0.04 m thickness would be necessary to maintain the waste maximum temperature below 1000 C, in deep space.

3.1.4.4 Waste Canister, Postfabrication

Having determined a workable preliminary design for deep space operation, the remainder of the waste canister thermal analysis is concentrated on maintaining the thermal limits throughout the various stages, culminating in space transport. The first of these is an analysis of the behavior of the canister after fabrication, up to a point where it has reached steady-state in a cooled, shielded container.

It is assumed that during the transition periods the waste temperature may increase to 900 C. Assuming this temperature as an initial condition, a transient analysis was performed using TRUMP, with the same input parameters of Table 3-1. However, instead of removing heat by radiation into space, the canister was assumed to be cooled by natural convection in air after heating. As an estimate of the thermal transient, the surface convection coefficient was assumed to be 11.3 W/m^2-C at all surface temperatures, with the ambient temperature being 38 C. Radiation to this sink was also included using an emissivity of 0.7 for the canister. Figure 3-3 shows the temperature transient after fabrication for various portions of the waste canister.

Results indicate that if no auxiliary cooling is used, the waste centerline temperature will reach 1000 C in less than 4 hours.

Aside from the variations in material parameters discussed in Section 3.1.4.3 the only variable significant to the transient behavior of the canister is the surface heat-transfer coefficient. However, the value chosen is typical of the values calculated for natural convection, air (5.6-28 W/m^2-C)[3-11]. No other cooling mode was examined, since it was felt that either the canister would be placed in storage or loaded for transport immediately (a matter of hours) after fabrication. Insofar as the canister is concerned, external cooling in a transport mode or storage mode is identical.

3.1.4.5 Waste Canister With Shielding, External Cooling

Since this analysis is concerned with the transportation of the waste canister, only the external cooling required by a shielded container designed for eventual terrestrial shipping will be examined (rather than on-site storage methods). After the canister has left the waste loading area it must be cooled within four hours or excessive temperatures will be reached in the center of the waste. The cooling requirements can be based on two conditions: (1) steady-state (external cooling, with shield), and (2) transient (post-fabrication to shielded container).

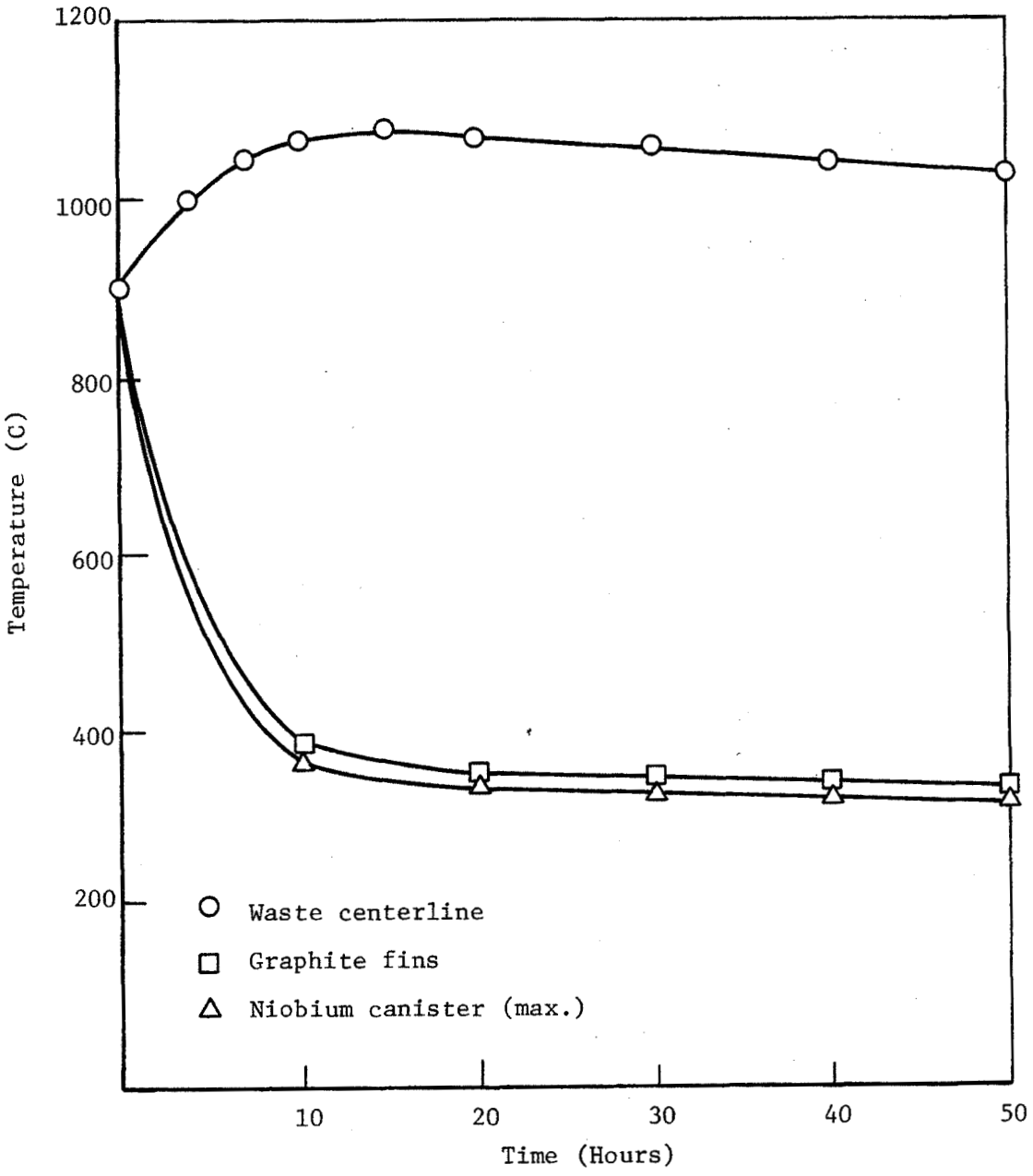

FIGURE 3-3. TEMPERATURE TRANSIENT IN WASTE CANISTER -- POSTFABRICATION

The first condition dictates the long-term cooling requirements to maintain the waste canister at an acceptable thermal level, while the second is a function of how long the canister may experience a lack of auxiliary cooling. A steady-state determination of the cooling requirements was made using the TRUMP code and data from Tables 3-4 and 3-5. Initial studies were directed toward cooling the canister/shield system by introducing a liquid or gas coolant into the outer shield. However, the thermal resistance of the gap between the canister wall and shield inner surface could not be overcome, and the waste centerline temperature rose above the temperature limit. An acceptable means of cooling is to apply the coolant directly to the canister wall. The effective steady-state heat-transfer coefficient on the canister surface should be approximately 30 W/m^2-C, to maintain a centerline temperature of 1000 C. The coolant may be introduced into the gap, or coolant channels may be incorporated in the canister walls. The latter would permit the canister to be cooled even during the waste loading operations.

Although the above cooling capacity is sufficient in the steady-state condition, it is not adequate to cool the waste centerline temperature after periods of transient heating when auxiliary cooling is not available. However, the cooling load could be increased to maintain limits for the time period necessary, after which the steady-state cooling requirements can be resumed. For example, preliminary estimates indicate that an interim cooling rate of 2.3 times steady-state would be sufficient if the canister cooling begins one hour after reaching 900 C. It should not be difficult to achieve the necessary heat-transfer coefficients with air cooling, provided means of distributing air-flow uniformly across the entire canister surface can be achieved. Note that the above assumptions neglect any end surface cooling.

3.1.4.6 Waste Canister in Transit

The results of the previous analysis indicate that, as long as auxiliary cooling can be maintained at the canister surface, the waste canister is isolated from the effects of outer transport containers, assuming, of course, that no external heat loads are encountered, and that the canister goes without cooling for no more than 2-3 hours between connections. Obviously, if accident conditions cause the loss of auxiliary cooling and the input of heat from an external source (such as the regulatory hypothetical fire accident) the established 1000 C maximum temperature will be exceeded in a short time. Further analysis must be performed to predict maximum temperatures of the waste and container materials to evaluate the hazards of this type of accident.

3.1.4.7 Summary

The limitations in launch payload requirements impose the use of internal fins in the high-level waste canister as a means of lowering the waste centerline temperature. A four fin arrangement may not be an optimum canister design; refined analyses can readily determine which combinations do form an optimum design (fin material, thickness, interval, etc.)

It was assumed in this study that the minimum requirements of the canister would include the limitation of waste maximum temperature to 1000 C, with no auxiliary cooling in space. Conversely, the design considered does not meet this temperature restriction under passive cooling while within various shielding and transport structures and active cooling systems will be necessary except during brief transfers. Analyses have shown that adequate cooling can be achieved with primary heat-transfer fluids of either liquids or gases.

3.1.5 Proposed Materials

The selection of materials considered for use as components (cooling fins, canister walls, radiation shield, and shipping cask) of the high-level waste package is discussed below (Northrop has selected stainless steel as the major constituent for the cocoon). The selection here has been preliminary in nature.

3.1.5.1 Cooling Fins

Candidate materials for cooling fins are: Pyrolytic graphite, copper, steel, and aluminum. The selection of these candidate materials was based upon: high thermal conductivity, fabricability, low density, low cost, high corrosion resistance, and shielding ability. Of these selection criteria, high thermal conductivity is the most important. Few materials have as high a thermal conductivity as the graphite. Second best is copper, which is a factor of 2 to 4 times lower in value. The machinability of all candidate materials is good. Except for graphite, other materials either have low melting points (aluminum, copper) or low conductivities (steel). Consequently, graphite is the most favorable. One potential drawback is the anisotropic nature of graphite. This factor is partly compensated by the large contact surface area provided in the design. Availability of this material in the quantities required must be determined.

3.1.5.2 Canister Walls

Candidate materials for the canister walls are: stainless steel, niobium, Inconel, and Hastelloy. The selection of these candidate materials was based upon: high thermal conductivity, corrosion resistance, shielding ability, and impact strength. All of these selection criteria are of equal importance with the possible exception of impact strength, which is secondary. Properties of stainless-steel, Inconel, and Hastelloys are about the same. Niobium has a higher conductivity and lower heat capacity than the rest, but lacks equivalent corrosion resistance in that it oxidizes at 200 C. However, special coatings can prevent this phenomenon. For this study, it was felt that the higher cost of niobium would be justified by its superior thermal properties. The materials property data of interest here are compared in Table 3-6.

3.1.5.3 Radiation Shield

Candidate materials for the radiation shield are: depleted uranium, lead, and steel. The selection of these candidate materials was based upon: shielding ability, low weight, and fabricability. The most efficient shielding material above is uranium, followed by lead. The equivalent steel shield would outweigh either lead or uranium, and result in a bulkier package. Lead has the disadvantage of being visco-elastic (resulting in lead "slump" under normal and accident impact loadings) and has a low melting point. Uranium is anisotropic and generally is not as ductile as steel or lead, although these are minor considerations unless impact resistance is important. To minimize weight, therefore, uranium was chosen as the radiation shield material. Probably an alloy such as U-2 w/o Mo should be used owing to its better strength when compared to unalloyed uranium.

TABLE 3.5. INPUT PROPERTIES OF WASTE CANISTER SHIELD AND OUTER WALL DESIGN

Property	Temperature (°C)	Uranium Shield	Outer Wall (304 SS)	Coolant	
				Liquid	Air
Density (kg/m^3)	all	19,000	7,820	1,000	0.96
Heat Capacity (W-hr/kg-C)	4.4	0.0324	0.13	0.57	
	38				0.283
	227	0.0376			
	258				0.291
	493	0.0471			
	660	0.0576			
Conductivity (W/m-C)	0		13.3	0.5	
	4.4	21.6			
	38				0.024
	100		15.7		
	171	25.6			
	258				0.036
	300		18.2		
	782	38.2			
	1000		26.9		
Emissivity	all	--	0.7	--	--

TABLE 3-6. CANISTER WALL CANDIDATE MATERIALS

	Thermal Conductivity (W/mC)	Coefficient of Thermal Expansion (cm/cm/C) x 10^{-6}	Tensile Strength (538 C) N/cm^2	Yield Strength (538 C) N/cm^2	Elongation, percent (in gage length)
304 SS	16.2	5.3	38,000	9,600	43
Niobium	47.6	4.8	45,000	38,000	15
Inconel 625	9.8	3.9	73,000	26,200	60
Hastelloy B	12.24	3.1	78,300	33,600	55

3.1.5.4 Shipping Cask

This structure will be little different from "conventional" shipping containers. The primary function of the shipping cask is to protect the waste canister/shield package in transit and to provide additional radiation shielding. A preliminary concept calls for steel inner and outer shells, with shielding material (lead) sandwiched in between, and impact absorbers added externally, as at the ends. Connections for external cooling will be included. Impact materials range over a wide variety: honeycomb, metal foams, low-density wood, fins, etc. A definite choice was not pertinent to this phase of the study.

3.1.6 Problems Associated with Overall Container System

Remote handling facilities will be required for loading the waste into the canister, closing and inspecting the canister, and inserting the contained waste into the shield assembly. Once the shield is in place, limited direct handling may be conducted but further shielding by a shipping cask will be required to allow transportation over unrestricted areas.

The heat generation rate will require nearly continuous cooling, allowing for a temperature rise only when the container is being transferred from one transportation mode to another. The compatibility of all cooling systems is a necessity. The cooling problem can be met most easily if the cooling can be incorporated directly into the canister walls. This would reduce the interfaces each time the canister is transferred from one transportation mode, or storage facility, to another.

The possibility of using the radiation shield outer wall as part of the cocoon should be studied (see Figure 3-4) to determine effects on cocoon design; e.g., reliability of cocoon fabrication if ends are added to cocoon mid-section after transport to launch site.

3.2 Handling and Transportation

3.2.1 Operational Scenarios

Using the concept for the waste package previously described, the various handling steps are presented in the following sections.

3.2.1.1 Reprocessor

Loading of the waste container, a refractory metal canister with an L/D of about one, is accomplished in a hot cell type facility. The operation consits of loading, welding of cover, leak testing, decontamination, and transfer to a clean area. All operations are accomplished remotely by machines or operator-controlled manipulators.

In the clean area the waste container is loaded into the shield-cocoon unit. Here the cocoon unit is basically an outer shell for the shielding with attachment points for the aerodynamic portions (to be installed later). Cooling passages are integral with the canister. Depending on timing, the cooling system is connected during loading of the canister, immediately after loading into the cocoon-shield package (CSP), or after the CSP is loaded into the shipping cask. For this case it is assumed that the CSP is not casked immediately.

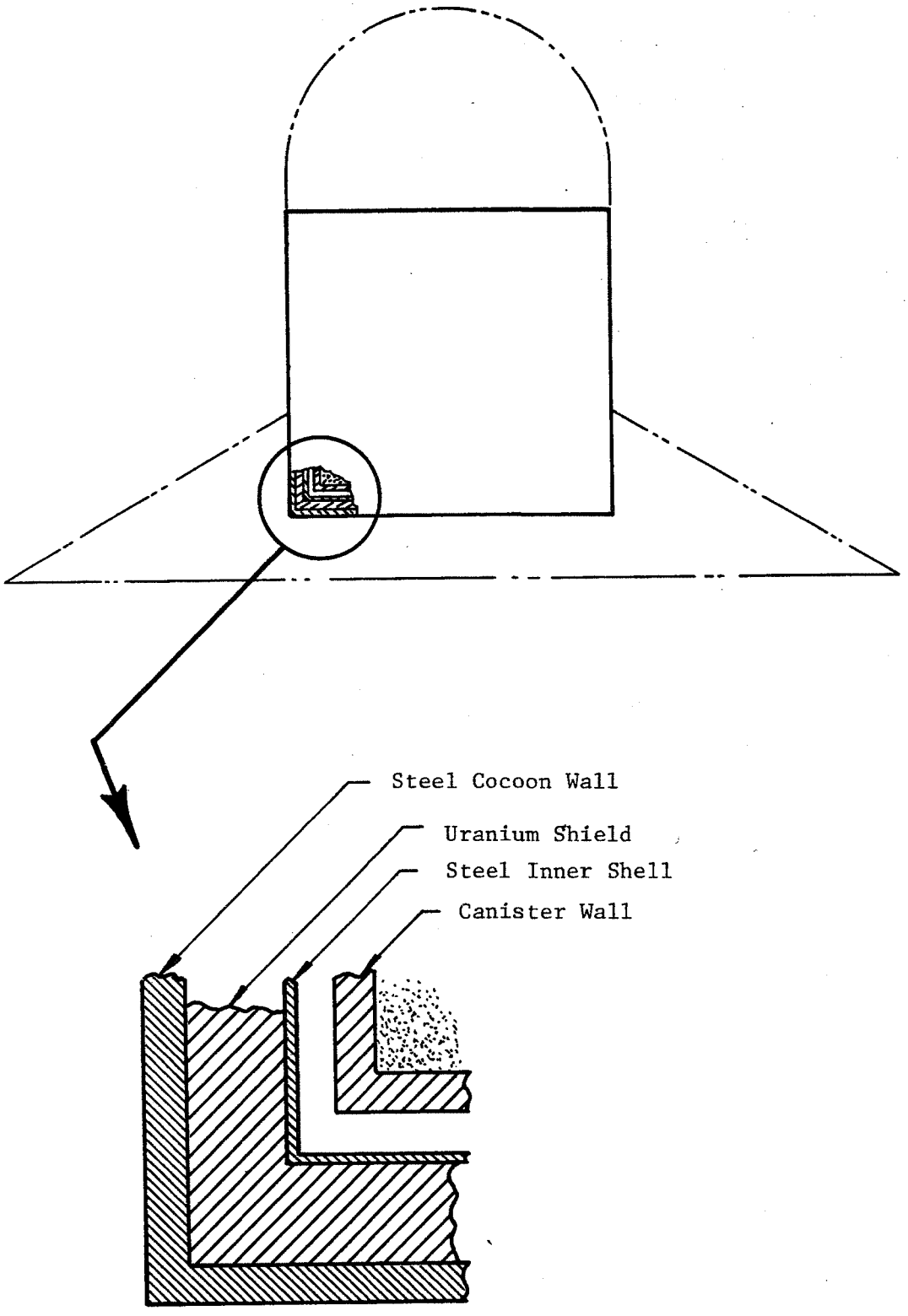

FIGURE 3.4. SHIELD-COCOON PACKAGE CONCEPT

With the waste canister in place, the CSP cover is positioned and sealed (probably by bolts). The cooling unit is attached, checked for leaks and operation begun. The CSP is transferred to a storage area or to the cask loading area. The operation described here is remote until the cover is installed and then essentially hands-on after that time.

The cask, which is primarily an impact and accident protection package, but must also incorporate additional shielding, is loaded next in the handling sequence. The storage area cooling unit is disconnected. The CSP is placed in the cask, the cover is installed, and the package is loaded onto the transporter. The cask cooling system is connected and the entire unit is inspected, monitored for radioactivity, and released for shipment.

At each step in the preceding handling scenario there must be provisions for faulted conditions, for example, leaky waste container lid, inoperable cooling system, etc. Storage and rework capabilities must be included in the facility design. These possible steps are not included in this or subsequent scenarios.

3.2.1.2 Transportation from Reprocessor to Receiving Facility at Launch Site

The options for transportation are dependent upon the location of the reprocessing facility and the launch site. A combination of transportation modes is conceivable; however, it might involve an added interface in handling the container.

The options for transportation between the reprocessing facility and the launch site are:

(1) Highway truck

(2) Rail car

(3) Barge or ship

(4) A combination of the above.

The characteristics of the HLW and the cooling requirements are such that the shipping cask and container weight probably will exceed the allowable highway weights by a factor of 1-1/2 to 2. It is possible, given access to a navigable waterway, that special trailers could be used to transport overweight casks onto a barge without traveling on public highways. In a similar manner, special rail cars could also be transported by barge for part of the trip. It is not likely that a reprocessing plant to launchsite shipment can be made without involving some form of trailer or rail car.

The use of special rail cars appears to offer the greatest flexibility for:

(1) Reprocessing facility location

(2) Launch site location

(3) Alternate routes

(4) All weather movements

(5) Anticipated weights.

3.2.1.3 Receipt of Cask at Receiving Facility

The cask will be delivered to the Receiving Facility and offloaded from the transporter. The cask is opened and the CSP is inspected and removed. It may be necessary at this point to attach a temporary neutron shield to the CSP which will remain until loaded aboard the Shuttle. During this process the cooling system is disconnected and the CSP is connected to the facility cooling unit. The cask and its cooling unit are returned to the reprocessor.

The Receiving Facility should be in a building which would minimize spread of contamination in the event of faulted conditions. However, it need not incorporate remote handling facilities. There should be equipment to cope with various package problems, leaks, cooling system failures and the like. The handling area should be designed to facilitate decontamination should such activities be required. Systems should be available to complete the assembly of the cocoon by attaching the nose and tail assemblies and to perform all inspections and system tests.

3.2.1.4 Preparation for Launch

This scenario includes transporting the shielded waste package in the cocoon from the receiving facility to the payload changeout room (PCR) and repositioning the PCR to make the transfer of the package to, and installing in, the Shuttle. The waste package will be loaded aboard the ground transporter, the auxiliary cooling will be disconnected, and the package will be transported to the PCR. With the transfer of the package from each facility to the next it will be necessary to disconnect and reconnect the cooling system within a minimum time interval. For contingencies, it may be desirable to have a portable cooling system which can be used to prevent overheating of the waste package. Within the PCR, the package will receive the final preparations, it will be raised to the proper elevation, the PCR will be rotated into position and the waste package within its cocoon will be transferred to the Shuttle. This transfer of the package will be accompanied by a transfer of the cooling requirements from the PCR to the Shuttle.

3.2.2 Potential Accidents During Handling

A number of potential accident situations exist during the various stages of handling from the initial stage of loading at the Reprocessing Facility on through the loading into the Shuttle at the launch site. The periods of higher risk (to the public and environment) appear to be during transportation and during the loading aboard the Shuttle. During the other handling periods the waste is within facilities that should limit spread of waste in the event of most conceivable accidents.

The normal handling and transportation of a radioactive materials package considers a variety of potential accidents. NRC/DOT regulations generally define the level of protection required to meet these accident situations. The packaging configuration for HLW disposal in space involves new concepts for the various levels of containment. Also, the consideration of launch windows for disposal missions, possible launch constraints (wind direction and general weather conditions), zero-g, and vacuum must be taken into consideration. A list of ten potential accidents is presented in Table 3.7. Each of these types of accidents is rated on the basis of the consequences of it occurring at each location. In many instances the particular accident situation does not exist and is noted as not applicable (NA). In other instances, the requirements of the NRC/DOT regulations are such that the consequences would be negligible.

TABLE 3-7. POTENTIAL ACCIDENTS INVOLVING TERRESTRIAL HANDLING OF NUCLEAR WASTE FOR SPACE DISPOSAL

Type of Accident	Consequences of Accident* at			
	Processing Facility	Transportation	Receiving Facility	Launch Site
Spill canister	In hot cell bothersome, but can be isolated	NA	NA	NA
Burn through weld while putting cover on	Repairable	NA	NA	NA
Drop canister	In hot cell can be isolated	NA	NA	NA
Puncture canister (no other containment)	In hot cell can be isolated	NA	NA	NA
Drop canister and shield	Can be outside of hot cell. May crack and spill	NA	NA	NA
Drop canister, shield and cocoon	Meets NRC/DOT regs. No problem	Meets NRC/DOT regs. No problem	Meets NRC/DOT regs. No problem	Probably scratch mission
Loss of coolant	4 hrs to hook up new system	4 hrs to hook up new system	4 hrs to hook up new system	Could scratch mission or go on hold
Fire	In hot cell? Outside H.C.--cask meets NRC/DOT regs., should survive	Outside H.C.--cask meets NRC/DOT regs., should survive	Outside H.C.--cask meets NRC/DOT regs., should survive	Catastrophic to Shuttle & launch system
Submersion	NA	Meets NRC/DOT regs. No problem	NA	NA
Puncture shipping cask	NA	Should meet NRC requirements	Should meet NRC requirements	NA

*Note: Accidents and consequences involving the actual launch and space operation are discussed in Section 4.4.

3.3 Packaging Criteria

The packaging of the High Level Waste being considered for this study differs from the usual concept of Type B quantities packaging. To begin with, the theoretical density under consideration is 4-6 g/cc which is higher than other state-of-the-art waste forms.

The packaging concept involves three levels of containment. The first level is a niobium cylinder holding the HLW. The side wall is approximately 2-1/2 cm thick and the ends 5 cm thick. The capacity is nominally 1.0 cubic meter with an L/D of about 1.0. The cover is welded on after compacting the contents. On the basis of 5.9 g/cc, the loaded container would weigh about 5900 kg (13,000 lb). The container would be provided with lifting lugs in order to insert it into the neutron/gamma shield/cocoon.

The second level of containment will provide the neutron/gamma shield. This containment will use depleted uranium (alloyed) as the shielding material. The inner and outer walls will be stainless steel to provide a low contamination surface as well as the first level of handling and transportation protection. The basic cooling lines will be an integral part of the package with appropriate attachments for "quick" connection to a standard auxiliary cooling system. The cooling system concept features auxiliary cooling sources at the processing plant, on board all transportation vehicles, at the launch site storage and change-out facilities, on the launch site loading equipment, and in the Shuttle vehicle. The cooling requirements after Earth orbit will be met by passive cooling.

An outer protective enclosure, designated the cocoon, will provide the launch abort and accidental reentry protection. Impact protection will be provided by approximately one inch of steel with an outer ablative coating if required (assumed by us—no supporting analysis). Additionally, the cocoon will be fitted with a reentry nose cone, an aerodynamic tail to assure the optimum reentry attitude and a parachute system to lower its free fall velocity prior to impact on the surface. Cocoon surfaces will provide the principal abative material. Because of their configuration they will not be shipped as a part of the HLW containment package, but will be attached at the launch site change-out facility. The cocoon will be the outer layer of the package that will be loaded into the Shuttle. If it becomes necessary to abort the mission during launch, the cocooned package will be ejected to fall into the sea. (Consideration of recovery is to be made by NASA/Northrop.) The cocoon will be the outer layer in the event of an accidental reentry from orbit. Upon arrival at the Earth orbit, and the subsequent offloading of the 3-axis stabilized cocoon system containing the waste canister, an orbit transfer vehicle (OTV) will rendezvous and remove the waste canister from the cocoon and radiation shield. The cocoon and shield will be returned to Earth in the Shuttle, for reuse, as the OTV transports the waste to its intended space destination.

The third level of containment for ground transportation will be a cask designed to provide accident protection. It will also be required to provide additional gamma shielding since that provided by the uranium shield will not meet the NRC/DOT regulations as summarized hereafter. The cask will not be used for storage other than on a temporary basis at a processing plant awaiting movement, or in a receiving area at the launch site. This cask, and its vehicle, will be equipped with an auxiliary cooling system and possibly, a backup system as a safety factor. Connections between the cooling system and the cooling coils in the canister will be made through the cocoon and will be designed so as to require a minimum amount of time to break and make, <4 hours. The system shall be capable of lowering the container outer wall temperature sufficiently to allow at least a 4-hour passive cooling period between cooling system hook ups. A projected mass of 36,000 kg (80,000 lb) for the cask and its contents and the auxiliary cooling systems indicates that transportation will be by rail or barge or both.

3.3.1 Normal Ground Transport to Launch Site— A Summary of NRC/DOT Regulations

The packaging of radioactive material for transport and the transportation of radioactive material under certain conditions is defined in 10CFR Part 71.[3-12] The pertinent parts include Section 71.5, "Transportation Of Licensed Material", which delineates the applicable Department of Transportation regulations relating to packaging, marking and labeling of the packages, loading and storage of packages, placarding of the transportation vehicle, monitoring requirements and accident reporting; also subpart C, "Package Standards"; Section 71.35, "Standards For Normal Conditions Of Transport For A Single Package" and Section 71.36, "Standards For Hypothetical Accident Conditions For A Single Package". Additionally, the Appendices A and B to 10CFR-71 describe normal conditions of transport and hypothetical accident conditions that produce thermal and mechanical loads which serve as the structural bases for the packaging of radioactive material for transport. Appendix C to 10CFR-71 describes the transport grouping of radionuclides. The Regulatory Guide 7.6 of the U.S. Nuclear Regulatory Commission additionally describes the design criteria acceptable to the NRC staff for use in structural analysis of the containment vessels of Type B packages used to transport irradiated nuclear fuel. Regulatory Guide 7.8 of the NRC presents a set of initial conditions that is considered acceptable by the NRC staff for use in the structural analyses of Type B packages used to transport irradiated nuclear fuel. The values in that set supplement the normal conditions and the hypothetical accident conditions of the regulations in forming a more complete basis from which stuctural integrity may be assessed.

It should be noted that the concept for the packaging of HLW deviates from the customary configuration and therefore will undergo additional scrutiny and review before license approval.

3.3.2 Accident Conditions

The accident conditions to be met in the design of the HLW package for surface transportation are described in Appendix B to 10CFR Part 71. Because the HLW packaging differs from the usual structural and shielding concept, it is possible that the NRC and the DOT will create separate requirements. The unique handling requirements for the pre-launch loading into the Space Shuttle, the Earth orbit extraction from the cocoon and shield, and the preparation for the journey into space are not defined in existing regulations. The existing 30 feet drop height requirement may be wholly inadequate for a loading gantry 60 to 100 feet above the ground. There will also have to be consideration for the potential of HLW dispersion in the orbit station area if one of the containers should be punctured.

3.4 Transport Model Compatibility

3.4.1 Compatability with NRC/DOT Requirements

The basic inner canister of coated niobium furnishes the first level of structural protection and sealed containment. The gamma shielding is provided by a uranium shield which is essential to the handling of the inner container at all times after loading is commenced. The cocoon provides structural integrity for both normal transportation and atmospheric reentry and splashdown. The canister is designed to be capable of passive cooling after Earth orbit, but requires an auxiliary cooling system during the ground transportation, storage, pre-launch and launch phases.

The CSP in a shipping cask which provides impact protection and additional radiation shielding should be capable of meeting all NRC and DOT requirements for shipments of radioactive material. The greatest liability to the licensing of the system is its dependence on auxiliary cooling to maintain acceptable internal temperatures.

3.4.2 Concept Compatibility with Prelaunch/Launch Systems

The CSP concept is based on the use of a bare minimum, first level containment wholly dependent upon the outer containment for shielding and accident protection.

The prelaunch/launch phase is defined as starting with the final assembly of the CSP with the flight cooling system in the storage area. At that time the CSP is disconnected from the storage area cooling system and is connected to the transporter cooling system. The launch phase is taken as that point at which the flight cooling system is inserted into the Shuttle orbiter and connected to the Shuttle's on-board systems.

Thus, there are a number of coolant system interfaces with various prelaunch/launch systems. The remaining interfaces will be for package attachment, cocoon ejection in the event of a post-launch abort and any required diagnostics.

Section 3 References

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4.0 ENVIRONMENTAL ASSESSMENT

The purpose of this preliminary environmental assessment was to identify and assess the potential environmental impacts of space nuclear waste disposal activities (see Section 1.5). This preliminary effort is the first step in the environmental assessment of space nuclear waste disposal. The long- and short-term environmental issues that relate to both terrestrial and space nuclear waste disposal undoubtedly will be critical factors in deciding which route will be followed.

The following sections describe the approach used to identify, prioritize (for study), and assess the various environmental impacts that could result from a nuclear waste disposal activity in space. Preliminary analysis is presented on those areas which are probably the most critical for the program. Emphasis has been placed upon the evaluation of hypothetical worst-case events, such that design and operational procedures are eventually chosen which would preclude the occurrences of such events. An indepth "credible" environmental assessment of a preferred disposal concept is not possible until better program definition is achieved. The preliminary analysis presented here, concerning the hypothetical worst-case events, is not intended to be used for comparisons with terrestrial options; however, it is solely to aid in the choice of space disposal design and operational alternatives which provide the least risk to man.

4.1 Identification of Possible Impacts

The first part of the environmental assessment involved the identification of all possible environmental impacts which would be expected to result from both normal (planned) and postulated abnormal events (accidents or other unplanned events) peculiar to a space-based nuclear waste disposal program.

The program was broken down into three major activity areas: (1) post-reactor processing, (2) terrestrial transport, and (3) space transport. Post-reactor processing involves all of the activities necessary to process spent fuel rods from light water nuclear reactors and to prepare the desired waste package which will then be shipped to the launch site. Terrestrial transport involves the shipping of the waste package to the launch site by appropriate means. The likely modes include railroad and ship. Space transport involves all of the activities associated with the waste package from the time it is received at the launch site until it is put to its final space disposal/storage destination.

Program phaseout and decommissioning was also identified as a program activity area. Although this activity area was not considered important in this effort, future efforts should expand and develop the environmental considerations of this activity.

The environmental effects areas considered in identifying possible environmental impacts were as follows:

- Air quality in the lower atmosphere (troposphere)
- Air quality in the upper atmosphere (stratosphere, mesosphere, ionosphere, and magnetosphere)
- Water quality (fresh, estuarine and marine)

- Land quality (earth, soils, etc.)
- Noise (including sonic booms)
- Water use
- Land Use
- Materials and energy use
- Effects on Ecosystems
- Human health and safety
- Culture
- Space.

Environmental impacts that were identifed for both normal and postulated abnormal events for each of the three major program activity areas are listed in Table 4-1. Since it was not possible to evaluate all of the impacts identified in this assessment, each of the impacts required study prioritization (see Section 4.2 for definition of prioritization criteria).

4.2 Impact Study Prioritization

Study prioritization criteria were developed so that the more important unknown issues could be given the needed attention in this preliminary environmental assessment. Study prioritization criteria were defined as follows:

Study Priority	Description
1	*Very important* — heavily a function of system design and operation—not much information available—is generally expected to have a major adverse impact, if it occurs
2	*Important* — information is available—may have a significant impact, if it occurs
3	*Somewhat important* — information is or is not available—impact is not expected to be significant, if it occurs
4	*Not important* — information may be available—impact is not expected to be significant, it if occurs.

A group having a wide range of expertise (ecology, health physics, nuclear engineering, aerospace engineering and environmental engineering) exercised a uniform participative procedure to assign priorities to all of the possible impacts listed in Table 4-1. The final results of this prioritization are indicated in the table. Issues other than those listed in the table were also identified and prioritized.

Priority No. 1 study areas concerned with normal operations were: a brief review of expected impacts from normal program operations including some consideration of siting factors, political/international implications of a U.S. or internationally operated space-based disposal program, and a brief assessment of the integrity of space storage/disposal activities.

TABLE 4-1. IDENTIFICATION AND PRIORITY OF ENVIRONMENTAL IMPACTS FROM A NUCLEAR WASTE DISPOSAL PROGRAM IN SPACE

AIR QUALITY LOWER ATMOSPHERE

NORMAL	ABNORMAL
POST-REACTOR PROCESSING	**POST-REACTOR PROCESSING**
CHEMICAL PROCESS RELEASES (3)	ACCIDENTAL CHEMICAL RELEASES (3)
RADIOACTIVE RELEASES (2)	ACCIDENTAL RADIOACTIVE RELEASES (2)
ENERGY CONSUMPTION RELEASES (3)	DECONTAMINATION ACTIVITIES (3)
CONSTRUCTION OF NEW FACILITIES (3)	
TERRESTRIAL TRANSPORT	**TERRESTRIAL TRANSPORT**
VEHICLE EMISSIONS (3)	ACCIDENTAL RADIOACTIVE RELEASES (2)
CONSTRUCTION OF NEW FACILITIES (3)	ACCIDENTAL CHEMICAL RELEASES (process chemical transport) (3)
	DECONTAMINATION ACTIVITIES (3)
SPACE TRANSPORT	**SPACE TRANSPORT**
LAUNCH VEHICLE EMISSIONS (2)	PROPELLANT SPILLS/FIRES (2)
CONSTRUCTION OF NEW FACILITIES (3)	CATASTROPHIC LV FAILURES (2)
PRELAUNCH/POSTLAUNCH EMISSIONS (3)	ACCIDENTAL RADIOACTIVE RELEASES (1)
OTV DEVELOPMENT TESTS (3)	• PRELAUNCH/POSTLAUNCH ACCIDENT (2)
LV DEVELOPMENT TESTS (3)	• LAUNCH ACCIDENT (1)
ENERGY CONSUMPTION RELEASES (3)	• REENTRY ACCIDENT (1)
	• ABORT ATTEMPT FAILURE (1)
	DECONTAMINATION ACTIVITIES (3)

AIR QUALITY UPPER ATMOSPHERE

NORMAL	ABNORMAL
POST-REACTOR PROCESSING	**POST-REACTOR PROCESSING**
NIL (4)	NIL (4)
TERRESTRIAL TRANSPORT	**TERRESTRIAL TRANSPORT**
NIL (4)	NIL (4)
SPACE TRANSPORT	**SPACE TRANSPORT**
LAUNCH VEHICLE EMISSIONS (2)	ACCIDENTAL RADIOACTIVE RELEASES (1)
OTV EMISSIONS (3)	• OTV REENTRY (1)
	• LV FAILURE/EXPLOSION (1)

EACH ACTIVITY SUBDIVIDED INTO DISCUSSIONS OF (if appropriate)

- STRATOSPHERE
- MESOSPHERE
- IONOSPHERE
- MAGNETOSPHERE

WATER QUALITY (Fresh, Estuarine, and Marine)

NORMAL	ABNORMAL
POST-REACTOR PROCESSING	**POST-REACTOR PROCESSING**
CHEMICAL PROCESS RELEASES (3)	ACCIDENTAL CHEMICAL RELEASES (2)
RADIOACTIVE RELEASES (2)	ACCIDENTAL RADIOACTIVE RELEASES (2)
ENERGY CONSUMPTION RELEASES (3)	DECONTAMINATION ACTIVITIES (3)
THERMAL POLLUTION (3)	
CONSTRUCTION OF NEW FACILITIES (3)	
LOCAL WATER USE (3)	
TERRESTRIAL TRANSPORT	**TERRESTRIAL TRANSPORT**
VEHICLE EMISSIONS (3)	ACCIDENTAL RADIOACTIVE AND CHEMICAL RELEASES (2)
CONSTRUCTION OF NEW FACILITIES (4)	• ON LAND (into fresh water) (2)
	• OCEANS (cask collapse, etc.) (1)
	DECONTAMINATION ACTIVITIES (3)
SPACE TRANSPORT	**SPACE TRANSPORT**
LAUNCH VEHICLE EMISSIONS (3)	PROPELLANT SPILLS/FIRES (2)
CONSTRUCTION OF NEW FACILITIES (3)	CATASTROPHIC LV FAILURES (2)
ENERGY CONSUMPTION RELEASES (4)	ACCIDENTAL RADIOACTIVE RELEASES (Fresh & ocean water) (1)
OTV DEVELOPMENT TESTS (3)	• PRELAUNCH/POSTLAUNCH ACCIDENT (2)
LV DEVELOPMENT TESTS (3)	• LAUNCH ACCIDENT (1)
	• REENTRY ACCIDENT (1)
	• ABORT ATTEMPT FAILURE (1)
	DECONTAMINATION ACTIVITIES (3)

LAND QUALITY

NORMAL	ABNORMAL
POST-REACTOR PROCESSING	**POST-REACTOR PROCESSING**
CHEMICAL PROCESS RELEASES (3)	ACCIDENTAL CHEMICAL RELEASES (3)
RADIOACTIVE RELEASES (2)	ACCIDENTAL RADIOACTIVE RELEASES (2)
ENERGY CONSUMPTION RELEASES (3)	DECONTAMINATION ACTIVITIES (3)
CONSTRUCTION OF NEW FACILITIES (3)	
TERRESTRIAL TRANSPORT	**TERRESTRIAL TRANSPORT**
VEHICLE EMISSIONS (particulates) (4)	ACCIDENTAL CHEMICAL RELEASES (3)
CONSTRUCTION OF NEW FACILITIES (4)	ACCIDENTAL RADIOACTIVE RELEASES (2)
	DECONTAMINATION ACTIVITIES (3)
SPACE TRANSPORT	**SPACE TRANSPORT**
LAUNCH VEHICLE EMISSIONS (2)	PROPELLANT SPILLS/FIRES (2)
CONSTRUCTION OF NEW FACILITIES (3)	CATASTROPHIC LV FAILURES (2)
ENERGY CONSUMPTION RELEASES (4)	ACCIDENTAL RADIOACTIVE RELEASES (1)
OTV DEVELOPMENT TESTS (4)	• PRELAUNCH/POSTLAUNCH ACCIDENT (2)
LV DEVELOPMENT TESTS (4)	• LAUNCH ACCIDENT (1)
	• REENTRY ACCIDENT (1)
	• ABORT ATTEMPT FAILURE (1)
	DECONTAMINATION ACTIVITIES (3)

Note: Numbers in parentheses refer to study priority--see Section 4.2.

(1) Very Important
(2) Important
(3) Somewhat Important
(4) Not Important

TABLE 4-1. (Continued)

LAND USE

NORMAL	ABNORMAL
POST-REACTOR PROCESSING	**POST-REACTOR PROCESSING**
CONSTRUCTION AND USE OF FACILITIES (3)	ACCIDENTAL RADIOACTIVE AND CHEMICAL RELEASES (2) (precludes use of land)
BUFFER ZONE (3)	DECONTAMINATION ACTIVITIES (3)
TERRESTRIAL TRANSPORT	**TERRESTRIAL TRANSPORT**
CONSTRUCTION OF FACILITIES (3)	ACCIDENTAL RADIOACTIVE AND CHEMICAL RELEASES (2) (precludes use of land)
USE OF TRANSPORTATION ROUTES (3)	DECONTAMINATION ACTIVITIES (3)
SPACE TRANSPORT	**SPACE TRANSPORT**
CONSTRUCTION AND USE OF FACILITIES (2)	ACCIDENTAL RADIOACTIVE AND CHEMICAL RELEASES (1) (precludes use of land)
LAUNCH VEHICLE OPERATIONS (2)	• PRELAUNCH/POSTLAUNCH ACCIDENT (2)
• SONIC BOOM (2)	• LAUNCH ACCIDENT (OTV or LV) (1)
• AIR QUALITY (3)	• REENTRY ACCIDENT (1)
• ACID RAIN (3)	• ABORT ATTEMPT FAILURE (1)
• REENTRY AND LANDING (2)	DECONTAMINATION ACTIVITIES (3)

WATER USE

NORMAL	ABNORMAL
POST-REACTOR PROCESSING	**POST-REACTOR PROCESSING**
PLANT OPERATION (3)	ACCIDENTAL RADIOACTIVE AND CHEMICAL RELEASES (precludes use of water resources) (2)
CONSTRUCTION OF NEW FACILITIES (4)	DECONTAMINATION ACTIVITIES (3)
TERRESTRIAL TRANSPORT	**TERRESTRIAL TRANSPORT**
CONSTRUCTION OF NEW FACILITIES (4)	ACCIDENTAL RADIOACTIVE AND CHEMICAL RELEASES (precludes use of water resources) (2)
FACILITY OPERATION (3)	DECONTAMINATION ACTIVITIES (3)
SPACE TRANSPORT	**SPACE TRANSPORT**
PRELAUNCH/POSTLAUNCH REQUIREMENTS (3)	FIRE CONTROL (3)
BASE REQUIREMENTS (3)	PROPELLANT SPILLS (3)
CONSTRUCTION OF NEW FACILITIES (3)	ACCIDENTAL RADIOACTIVE RELEASES (precludes use of water resources) (1)
OTV DEVELOPMENT TESTS (3)	• PRELAUNCH/POSTLAUNCH ACCIDENT (2)
LV DEVELOPMENT TESTS (3)	• LAUNCH ACCIDENT (OTV or LV) (1)
VEHICLE LAUNCH REQUIREMENTS (3)	• REENTRY ACCIDENT (1)
	• ABORT ATTEMPT FAILURE (1)
	DECONTAMINATION ACTIVITIES (3)

NOISE

NORMAL	ABNORMAL
POST-REACTOR PROCESSING	**POST-REACTOR PROCESSING**
PLANT NOISE (4)	EXPLOSION AT PLANT (3)
CONSTRUCTION OF NEW FACILITIES (3)	DECONTAMINATION ACTIVITIES (4)
TERRESTRIAL TRANSPORT	**TERRESTRIAL TRANSPORT**
VEHICLE NOISE (3)	DECONTAMINATION ACTIVITIES (4)
CONSTRUCTION OF NEW FACILITIES (3)	
SPACE TRANSPORT	**SPACE TRANSPORT**
VEHICLE LAUNCH NOISE (2)	CATASTROPHIC LV FAILURES (3)
OTV DEVELOPMENT TESTS (2)	PRELAUNCH/POSTLAUNCH ACCIDENTS (3)
LV DEVELOPMENT TESTS (2)	ABORT (different locations) (3)
CONSTRUCTION OF NEW FACILITIES (3)	ABORT ATTEMPT FAILURES (3)
SONIC BOOM – VEHICLE LAUNCH & REENTRY (2)	DECONTAMINATION ACTIVITIES (4)
	SONIC BOOM – UNPLANNED HARDWARE REENTRY (2)

MATERIALS AND ENERGY USE

NORMAL	ABNORMAL
POST-REACTOR PROCESSING	**POST-REACTOR PROCESSING**
PLANT OPERATION (3)	DECONTAMINATION ACTIVITIES (3)
PLANT DEVELOPMENT/CONSTRUCTION (3)	REPLACEMENT HARDWARE AND FACILITIES (3)
TERRESTRIAL TRANSPORT	**TERRESTRIAL TRANSPORT**
VEHICLE CONSTRUCTION (3)	DECONTAMINATION ACTIVITIES (3)
VEHICLE OPERATION (3)	REPLACEMENT HARDWARE AND FACILITIES (3)
CONSTRUCTION OF FACILITIES (3)	
SPACE TRANSPORT	**SPACE TRANSPORT**
FACILITY CONSTRUCTION (3)	DECONTAMINATION ACTIVITIES (3)
FACILITY OPERATION (3)	REPLACEMENT HARDWARE AND FACILITIES (2)
VEHICLE CONSTRUCTION (3)	
VEHICLE LAUNCHES (2)	
LV DEVELOPMENT (3)	
OTV DEVELOPMENT (3)	

TABLE 4-1. (Continued)

EFFECTS ON ECOSYSTEMS (TERRESTRIAL AND AQUATIC)

NORMAL

POST-REACTOR PROCESSING
- CONSTRUCTION OF NEW FACILITIES (3)
- RADIOACTIVE RELEASES (2)
- ENERGY CONSUMPTION RELEASES (3)
- CHEMICAL PROCESS RELEASES (3)
- THERMAL POLLUTION (3)

TERRESTRIAL TRANSPORT
- VEHICLE EMISSIONS (3)
- CONSTRUCTION OF FACILITIES (3)

SPACE TRANSPORT
- LAUNCH VEHICLE OPERATIONS (2)
- OTV DEVELOPMENT TESTS (3)
- LV DEVELOPMENT TESTS (3)
- CONSTRUCTION OF NEW FACILITIES (3)

ABNORMAL

POST-REACTOR PROCESSING
- ACCIDENTAL CHEMICAL RELEASES (3)
- ACCIDENTAL RADIOACTIVE RELEASES (2)
- EXPLOSION AT THE PLANT (3)
- DECONTAMINATION ACTIVITIES (3)

TERRESTRIAL TRANSPORT
- ACCIDENTAL CHEMICAL RELEASES (3)
- ACCIDENTAL RADIOACTIVE RELEASES (2)
- DECONTAMINATION ACTIVITIES (3)

SPACE TRANSPORT
- PROPELLANT SPILLS/FIRES (2)
- CATASTROPHIC LV FAILURES (2)
- ACCIDENTAL RADIOACTIVE RELEASES (1)
  - PRELAUNCH/POSTLAUNCH ACCIDENT (2)
  - LAUNCH ACCIDENT (1)
  - REENTRY ACCIDENT (1)
  - ABORT ATTEMPT FAILURE (1)
- DECONTAMINATION ACTIVITIES (3)

EACH ACTIVITY SUBDIVIDED INTO DISCUSSIONS OF (if appropriate):
- AIR QUALITY – UPPER/LOWER ATMOSPHERE
- *WATER QUALITY/USE (fresh water and oceans)*
- LAND QUALITY/USE
- NOISE AND SONIC BOOM

HUMAN HEALTH AND SAFETY

NORMAL

POST-REACTOR PROCESSING
- RADIOACTIVE RELEASES (2)
- ENERGY CONSUMPTION RELEASES (3)
- CHEMICAL PROCESS RELEASES (3)

TERRESTRIAL TRANSPORT
- *CHANGES IN TRAFFIC (3)*

SPACE TRANSPORT
- LAUNCH VEHICLE OPERATIONS (2)
- OTV DEVELOPMENT TESTS (3)
- LV DEVELOPMENT TESTS (3)

ABNORMAL

POST-REACTOR PROCESSING
- ACCIDENTAL CHEMICAL RELEASES (3)
- ACCIDENTAL RADIOACTIVE RELEASES (2)
- EXPLOSION AT THE PLANT (2)
- DECONTAMINATION ACTIVITIES (3)

TERRESTRIAL TRANSPORT
- *ACCIDENTAL CHEMICAL RELEASES (3)*
- ACCIDENTAL RADIOACTIVE RELEASES (2)
- DECONTAMINATION ACTIVITIES (3)

SPACE TRANSPORT
- PROPELLANT SPILLS/FIRES (2)
- CATASTROPHIC LV FAILURES (2)
- ACCIDENTAL RADIOACTIVE RELEASES (1)
  - PRELAUNCH/POSTLAUNCH ACCIDENT (2)
  - LAUNCH ACCIDENT (1)
  - REENTRY ACCIDENT (1)
  - ABORT ATTEMPT FAILURE (1)
- DECONTAMINATION ACTIVITIES (3)

EACH ACTIVITY SUBDIVIDED INTO DISCUSSIONS OF (if appropriate):
- AIR QUALITY - UPPER/LOWER ATMOSPHERE
- WATER QUALITY/USE (fresh water and oceans)
- LAND QUALITY/USE
- NOISE AND SONIC BOOM

CULTURAL

NORMAL

POST-REACTOR PROCESSING
- SITING FACTORS FOR PLANT (1)
- OPERATION OF PLANT (3)

TERRESTRIAL TRANSPORT
- *TRANSPORTATION METHOD AND ROUTE (2)*
- CONSTRUCTION OF NEW FACILITIES (2)

SPACE TRANSPORT
- LAUNCH VEHICLE OPERATIONS (2)
- OTV DEVELOPMENT TESTS (3)
- LV DEVELOPMENT TESTS (3)
- CONSTRUCTION OF NEW FACILITIES (2)
- SITING FACTORS FOR LAUNCH FACILITIES (1)

ABNORMAL

POST-REACTOR PROCESSING
- ACCIDENTAL RADIOACTIVE RELEASES (2)
- ACCIDENTAL CHEMICAL RELEASES (3)

TERRESTRIAL TRANSPORT
- *ACCIDENTAL RADIOACTIVE RELEASES (2)*

SPACE TRANSPORT
- ACCIDENTS - SPILL/FIRES (3)
- ACCIDENTAL RADIOACTIVE RELEASES (1)
  - PRELAUNCH/POSTLAUNCH ACCIDENT (2)
  - LAUNCH ACCIDENT (1)
  - REENTRY ACCIDENT (1)
  - ABORT ATTEMPT FAILURE (1)

EACH ACTIVITY SUBDIVIDED INTO DISCUSSIONS OF IMPACTS:
- DEMOGRAPHIC, SOCIAL AND ECONOMIC
- COMMUNICATIONS
- SCIENTIFIC INVESTIGATIONS
- HISTORICAL AND RECREATIONAL
- AESTHETICS

ENTIRE PROGRAM →
- POLITICAL/INTERNATIONAL (1)
- INTRUSIVE ACTS OF MAN (1)

SPACE

NORMAL

POST-REACTOR PROCESSING
- NONE

TERRESTRIAL TRANSPORT
- NONE

SPACE TRANSPORT, STORAGE AND DISPOSAL
- OTV EMISSIONS (3)
- ULTIMATE CONTAMINATION (also preclude use) OF
  - EARTH ORBITAL AREAS (2)
  - MOON (1)
  - PLANETS (3)
  - OTHER PLANETARY SYSTEMS (3)

ABNORMAL

POST-REACTOR PROCESSING
- NONE

TERRESTRIAL TRANSPORT
- NONE

SPACE TRANSPORT, STORAGE AND DISPOSAL
- ORBITAL ACCIDENT (2)
- ORBITAL DEBRIS (3)
- ORBITAL CONTAMINATION (1)
- LUNAR CONTAMINATION (1)
- PLANET CONTAMINATION (2)
- CONTAMINATION OF OTHER PLANETARY SYSTEMS (2)

Priority No. 1 study areas associated with postulated abnormal events (e.g., accidents or other unplanned events) were: accidents at sea involving the shipping cask or cocoon with the release of radioactive material, space system failures during boost and low-Earth orbital operations with the release of radioactive material into the Earth's biosphere, accidents in space (particularly on the moon), and the potential for intrusive acts of man.

These top priority study areas for both the normal program activities and postulated abnormal events are the subject of the following treatments. Also, suggested design and operational procedure criteria (Section 4.5), political and international issues (Section 4.6), and intrusive acts of man (Section 4.7) are discussed. Future assessment efforts should further develop these treatments, and expand to other areas of interest (e.g., definition of credible and incredible accidents, evaluation of accident probabilities, and evaluation of the risk to man).

4.3 Brief Environmental Assessment of Normal Operations

This section briefly assesses the relevant issues for the three major program areas that are related only to environmental impacts that are expected to result from normal or "planned" space nuclear waste disposal activities (see Section 1.5 for program description). Post-reactor processing and terrestrial transport activities will both be the responsibility of ERDA if a space disposal activity is put into operation. Also ERDA is currently sponsoring a considerable research effort in evaluating the environmental risks for these activities as they relate to terrestrial disposal of nuclear waste material. Little work has been done related to the environmental impact of space nuclear waste disposal. Therefore, emphasis here has been placed upon the environmental impact assessment of space transport activities as they relate to a nuclear waste disposal program in space.

4.3.1 Post-Reactor Processing

A considerable amount of information exists relative to the environmental impact of nuclear waste processing. Environmental studies of the Barnwell Nuclear Fuel Plant located in Barnwell, S.C., provide information related to the impacts that might be expected from the normal processing activities associated with Mix No. 3.[4-1 through 4-3] Environmental effects include thermal pollution in the local water systems, gaseous and liquid chemical releases, and radioactive material releases. Reference 4-4 (GESMO) provides considerable information related to the environmental effects projected for the mixed oxide fuel cycle. The References cited above indicate that normal plant operation will not cause any adverse effect upon people or the local environment.

Battelle Northwest Laboratories and other organizations are currently studying the environmental impact of both terrestrial nuclear waste disposal and the processing of nuclear fuel from LWR's. Information from these studies will be available in the near future, such that environmental impacts peculiar to off-baseline mixes (other than Mix No. 3—see Section 2.3) can be evaluated.

4.3.2 Terrestrial Transport

Normal activities associated with the terrestrial transport of nuclear waste from the processing facility to the launch site should not involve any significant radiological impacts to the environment. It is assumed that the container which houses the nuclear waste package adequately shields the public and workers from radiation and leakage (see Section 3.0). The environmental impacts from terrestrial transport, although insignificant, are a function of the mix chosen, and hence the amount of material that has to be shipped to the launch site. The larger the amount of space-disposable material, the larger are the total emissions that would result from the transport vehicles. Possible modes of transport involve truck, rail and ship. The combustion emissions from power plants that drive these vehicles are considered to be insignificant when compared to all types of emissions that result from the shipment of commodities throughout the nation and on the seas. Reference 4-5 provides a good background discussion of relevent issues related to the transport of nuclear materials. References 4-1 and 4-2 also provide additional information concerning the transport of nuclear materials.

4.3.3 Space Transport

This section briefly assesses the environmental impacts caused by normal space transport activity (see Table 4-1). Activities considered here include: launch site development, OTV development, Space Shuttle launch operations, OTV operations, ultimate space disposal of the nuclear waste, and energy requirements. Activities or environmental effects that are not treated here are not expected to have any adverse effects under normal conditions.

Baseline assumptions (as defined by NASA/MSFC) are that two Shuttle launches are required for the disposal of one payload containing 5500 kg of nuclear waste; one for the payload and its ancillary equipment (reentry cocoon, cooling system, pallet, etc.), the other for placing a fueled LH_2/LO_2 Orbit Transfer Vehicle (OTV) into orbit prior to rendezvous and docking of the OTV with the nuclear payload. The baseline waste mix is assumed to be Mix No. 3 in the calcine form. Important space transport activities and associated impacts are discussed where appropriate.

In summary, the normal activities of space transport and disposal of nuclear waste in space are not expected to pose a significant adverse impact to the quality of the human environment, either in the next two decades or in the long-term future*, if baseline approaches are assumed. Mix No. 1 would likely pose significant environmental impacts even if launched from a remote site. Energy requirements for launch operations alone make serious consideration of disposing of Mix No. 1 unreasonable. Space Shuttle launch rates projected for other mixes do not appear to offer any significant environmental impacts. Impacts would be expected to be similar to those currently predicted for Space Shuttle operations at total launch rates of 60 per year (40 per year at Kennedy Space Center, Florida). Normal space disposal activities of the various mix options are not expected to have any significant adverse effects either to orbits or to celestial bodies. However, the use of a region of the Moon as a disposal/storage area would probably preclude the use of that region for future generations. It is expected that adequate siting studies, which consider all scientific, economic and cultural factors, will be made such that impacts affecting the future use of the Moon would be minimized. Political implications regarding the exclusive use of the Moon are discussed in Section 4.6.

*Accidents, however, could be significant. Section 4.4 discusses worst-case postulated accidents on Earth and in space; proper system design and procedures can practically eliminate the chance for these worst-case events. The treatment of credible accidents is expected to be the scope of future work.

4.3.3.1 Launch Site Development

The requirement for a new remote launch site or new facility construction at Kennedy Space Center (KSC) is dependent upon the nuclear waste mix and form chosen for space disposal. For purposes of discussion, the calcine waste form is considered here. For the five mixes assumed as alternatives in this report, and with the anticipated launch rates (see Table 4-3), certain environmental impacts caused by facility development and launch operations can be estimated. For normal operations, these factors give guidance to site selection.

Because of the lower launch rates, it is expected that nuclear waste disposal in space involving Mixes No. 4 and No. 5 could be handled at existing launch facilities at KSC; however, additional payload handling and storage facilities would be required. The construction of these facilities and the enforcement of the proper safeguard procedures would not be expected to pose any significant impacts to the KSC area or to the other ongoing space program activity.

Nuclear waste Mixes No. 2 and No. 3 would probably require a remote island launch site (or possibly a remote ocean-based platform) to minimize the expected launch impacts and other risks to man. Development of launch facilities at a remote tropical island in the South Atlantic Ocean would provide for minimum overflight of land during ascent to orbit, thus reducing the risk to man. Development of a launch site on a remote island (or launch platform) for the disposal of Mixes No. 2 and No. 3 would require facilities to handle annual Space Shuttle launch rates of 60 to 80 by the year 2000. If a launch complex were placed on a remote island, the environmental impacts to the island would be significant; however, when weighed against launching from nonremote areas located in other parts of the globe (e.g., U.S. coastal areas), the overall impact to the human environment would be less. Major impacts of normal operations on such an island might involve the following: the relocation of inhabitants, the destruction of vegetation and wildlife habitats, the extinction of local animal species, and the disturbance of archaeological sites. Site selection criteria could be used to minimize these to some extent.

Because of the extremely high launch rates, launch facilities needed to accommodate the disposal of Mix No. 1 would pose considerable environmental effects, regardless of launch site location, which forces the conclusion that the Mix No. 1 option is not feasible.

4.3.3.2 Orbit Transfer Vehicle (OTV) Development

In most nuclear waste disposal analyses to date, it has been assumed that the OTV will be a hydrogen/oxygen fueled chemical stage sized to the maximum payload carrying capability of the Shuttle (29,500 kg). Development activities associated with this OTV are not considered to have any significant environmental consequences. The only environmental concern associated with the ground-based development activities of a hydrogen/oxygen OTV would be the noise generated during engine and engine component testing. The majority of these development tests would probably take place at NASA's National Space Technology Laboratory (NSTL), located in southern Mississippi. Adequate noise buffer zones currently exist at this facility, so that noise impacts to inhabited areas are minimal.

OTV development activities would also require development flight tests. These tests would be necessary to verify overall system function. Other than the expected environmental impacts from normal Space Shuttle launches (see Reference 4-6), OTV flight tests simulating a nuclear waste disposal mission may cause some temporary effects to the ionosphere (see Section 4.3.3.4).

The development of an OTV employing an alternate propulsion technology is possible (see Section 1.5). These include: solid propellant, solar electric propulsion (SEP), nuclear electric propulsion (NEP), and solar sail propulsion (SSP). The various environmental concerns for ground and flight tests for these alternatives (including the LH_2/LO_2 baseline) are shown in Table 4-2. From an environmental impact point of view* the OTV alternatives can be rated (subjective) from the most favorable to the least favorable, as follows: LH_2/LO_2, SSP, SEP, solid propellants and NEP. LH_2/LO_2 is rated ahead of SSP because the SSP (and perhaps SEP also) will probably require the development of a small propulsive kick stage to place the SSP into a high enough Earth orbit that it can operate effectively. Any extensive use of SEP or NEP for nuclear waste disposal operations would likely require the Hg propellant to be replaced by a less efficient, but nontoxic propellant.

4.3.3.3 Space Shuttle Launch Operations

Space Shuttle launch operations and related activities required for the disposal of nuclear waste in space will have some adverse effects upon the environment, although not necessarily significant. These effects have been studied and are documented in References 4-6 through 4-11. For Space Shuttle launches, adverse effects are: potential for acid rain events; possible exposure of the local population to potentially toxic emissions (HCl, Al_2O_3 and Cl_2); launch noise; sonic booms resulting from launches (over the ocean) and reentry of the Orbiter; a slight reduction in the stratosphere ozone concentration resulting in increased ultraviolet radiation, with possible secondary effects to people and ecosystems; and ionospheric effects which may result in localized short-term interruption of some radio communications.

The potential for some adverse effects and the magnitude of others increase with increasing launch rates of the Space Shuttle. Table 4-3 was generated to provide estimates of Space Shuttle launch rates as a function of mix for the calcine waste form. The table was constructed from data in Tables 2-3 and 2-4, assuming that: (1) two Space Shuttle flights (one for launching OTV, the other for launching the waste payload and its ancillary equipment) are required for disposal of each 5500 kg of nuclear waste, and (2) that a reasonable buildup of the launch rate is assumed during the first three years of operation, with a "steady" launch rate from 1987 through 1991.

Launch rates indicated in Table 4-3 for Mix No. 1 (reaching 1728 by the year 2000) imply that using the Space Shuttle vehicle for such a mission is not feasible.

Launch rates of 60 to 80 per year for Mixes No. 2 and No. 3 coupled with the planned 40 per year launch rate at KSC for other space program activities, would probably be unacceptable. The waste disposal for Mixes No. 2 and No. 3 would probably be environmentally superior if these missions are flown from a new remote island launch site.

Environmental impacts to human populations from normal Space Shuttle flights carrying nuclear waste payloads and OTVs out of a remote island launch site would not be as severe as would be the case if the flights were launched from KSC. Acidic rain, if created, would fall into the ocean with no noticeable effect on ecosystems. Noise impacts during launch would be limited to the life systems existing on the island. It is assumed that there will be no inhabitants on the remote island (island assumed to be small), except those included in program activity;

*These considerations do not take into account mission capacity. Certain OTVs have different performance and mission capacities which may alter the required Space Shuttle launch rate, thus effecting the overall environmental impact.

TABLE 4-2. ENVIRONMENTAL CONCERNS FOR OTV GROUND AND FLIGHT TEST DEVELOPMENT ACTIVITIES

Propulsion Technology--Propellant	Development Tests	
	Ground	Flight
Chemical		
Liquid Propellants--LH_2/LO_2[a]	Noise	Ionospheric Impacts
Solid Propellants--AP/Al/Binder	Noise, acid rain, emissions	Ionospheric Impacts
Solar Electric Propulsion--Hg	Propellant Handling	Earth Contamination
Nuclear Electric Propulsion--Hg	Propellant Handling Radiation Effects	Earth Contamination
Solar Sail Propulsion--N.A.[b]	None[b]	None[b]

(a) Other liquid propellants are possible, but generally not considered attractive from both safety and performance standpoints--examples are: LH_2/LF_2, N_2H_4/LF_2, and MMH/N_2O_4.

(b) SSP would likely require propulsive kick stage. See text.

TABLE 4-3. PROJECTED SPACE SHUTTLE LAUNCH RATES AS A FUNCTION OF NUCLEAR WASTE MIX, ASSUMING A CALCINE WASTE FORM

Year	Waste Available for Disposal (metric tons)[a]	Waste for Space Disposal (metric tons)	Number of Space Shuttle Launches[b] (Mix Option)				
			1	2	3	4	5
1985	1365	100	42	2			
1986	663	500	212	10	8	2	
1987	889	1443	614	28	24	6	
1988	1063	1443	614	28	22	8	
1989	1175	1443	614	30	24	6	2
1990	1282	1433	614	28	22	6	
1991	1379	1444	614	30	24	8	2
1992	1544	1544	658	30	24	6	
1993	1799	1799	764	36	30	8	
1994	2061	2061	878	42	32	10	2
1995	2376	2376	1010	46	38	12	2
1996	2768	2768	1178	56	44	12	2
1997	3144	3144	1338	64	52	14	
1998	3463	3463	1474	68	54	16	2
1999	3759	3759	1598	76	60	18	2
2000	4062	4062	1728	80	66	18	2
Totals	32792	32792	13950	654	524	150	16

(a) Data from Table 2-3, assuming optimistic waste availability.

(b) Calculated based upon multiplication factors in Table 2-4, a 5500 kg waste payload, and two Space Shuttle flights per payload.

therefore, to insure adequate safety from hearing loss, workers would be required to take proper precautions during launches—move inside buildings, wear protective devices over the ears, or maintain proper distances from the launch pad.

Sonic booms associated with the reentry of the Space Shuttle Orbiter upon completion of a disposal mission, may have adverse environmental implications (annoyance of people) if all flights return to KSC, regardless of the launch site. Ideally, it would be preferable to land the Orbiter on the remote island to minimize sonic boom effects on people. If a landing site, requiring at least 4.6 km of runway, were constructed in a new area—e.g., South America—inhabitants within the region of influence would likely be subjected to the annoyance of sonic booms. If possible, it therefore would be advisable for a new island launch site to have provisions for Orbiter landings.

The use of a remote island launch site would also reduce the number of people that would be potentially exposed to toxic Space Shuttle exhaust gases (HCl and Cl_2) and particulates (Al_2O_3). Emissions expected as a result of normal launches are well below guidelines for concentrations and doses of these pollutants so that no effects to healthy workers are expected.

A launch site located closer to or south of the Equator would provide less of an impact to the Earth's people and ecosystems as a result of ozone depletion in the stratosphere. HCl emitted at or south of the Equator results in less ozone depletion in the northern hemisphere when compared to using KSC as the launch site. Since the world's population and land mass are concentrated in the northern hemisphere, less effect on the Earth's total human population and ecosystems would be expected.

Launches (8 to 18 annual) of waste Mix No. 4 from KSC might be more acceptable, providing separate Orbiters and certain facilities are constructed to support waste disposal mission functions. Space users (including NASA itself) would probably not want to risk contamination of existing KSC Shuttle facilities. Contamination, as a result of a radioactive material release could put a halt to the major portion of the space program. The increase in overall Space Shuttle launches from 40 to 50 or 60 per year would not be expected to pose a significant change in the existing environments.

Mix No. 5 requires only two launches in any given year, and could also be launched using the KSC launch area. In fact, for these low launch rates the use of existing Shuttle facilities seems appropriate. A special nuclear handling and storage facility would have to be constructed at KSC to handle the Mix No. 5 disposal missions. Normal disposal missions requiring only two Space Shuttle launches per year would cause no noticeable change in the existing environment.

Ozone depletion would vary with the annual Space Shuttle launch rate. If one calculates the average launch rates for the last 10 years of the waste disposal program (1991–2000), the ozone depletion contribution that might be expected for the five mixes (starting with Mix No. 1) would be 3.5%, 0.18%, 0.14%, 0.04% and 0.01%, respectively. These estimates are based upon a 0.2% ozone depletion for 60 Space Shuttle flights per year[4–6], and the assumption that the relationship between launch rate and ozone depletion percentage is linear. Effects from a 0.2% ozone depletion (0.4% increase in biologically harmful ultraviolet radiation) may cause a slight rise in the incidence of skin cancer. Reference 4-6 reports that if any increase does occur, it must be small relative to the current U.S. incidence of about 300,000 cases per year and would not be detectable against the yearly fluctuations in reported cases. Most skin cancers are of the nonmelanoma variety (97%) and are rarely fatal.

The possible development of a different OTV, a different launch vehicle (e.g., alternate solid or liquid propellant booster or a new heavy lift vehicle) to replace the Space Shuttle vehicle, would most likely reduce the launch rates and the environmental impacts anticipated from the use of the baseline Space Shuttle and OTV during normal operations. As the program proceeds, there is no reason why system changes could not be made or new systems developed to increase mission reliability and reduce cost and environmental impact.

4.3.3.4 Orbit Transfer Vehicle (OTV) Operations

The environmental impact to the upper regions of the Earth's atmosphere caused by OTV operations is dependent upon the type of OTV employed. Chemical effluents from the operation of OTV's can cause a significant reduction in the local ion concentration in the upper regions of the ionosphere (low Earth orbit), thus effecting radio wave propagation. OTVs employing LH_2/LO_2, solid propellants and perhaps SEP and NEP, if operated at low enough altitudes are expected to cause such effects. The two chemical propulsion stages would have more of an impact because of the larger amount of material released in a given region. A solar sail OTV would probably require a chemical propulsive stage [perhaps an Interim Upper Stage (IUS)] to boost its orbit. Some impacts might be expected from the use of the IUS; none are anticipated from the solar sail.

Mercury, released from a SEP or NEP while operating inside of the Earth's bow wave, would enter the magnetosphere which would then in turn cause the material to be captured by the Earth's atmosphere at the poles (as a result of the mirroring effect), potentially causing increases in mercury concentrations in these regions. The use of a different propellant in the SEP and NEP would be expected to have significantly less of an environmental impact.

4.3.3.5 Space Storage/Disposal Operations

The impact at the destination environment caused by nominal operations of space nuclear waste storage/disposal schemes are considered in this section. The possible destinations are: high Earth orbits, heliocentric trajectories toward or away from the Sun, lunar surface, and solar system escape trajectories.

Because retrieval of waste can be considered as a possibility with the high Earth orbit and lunar destinations, "storage" options are described. Retrieval of waste is not considered viable with the other options.

4.3.3.5.1 High Earth Orbits

The storage of nuclear waste canisters in high Earth orbits would incorporate the following nominal operations: (1) delivery of waste canisters to low Earth orbit aboard the Space Shuttle and transfer to the OTV, (2) velocity impulse maneuver to high Earth orbit, and (3) circularization impulse maneuver and placement of canisters. The only possible environmental impact caused by normal operations once the waste package has arrived at the space destination is: (1) an increase in orbital debris (expended OTV and waste canister), and (2) the possibility of future reentry of the waste canister into the Earth's biosphere.

The storage of nuclear waste would not be expected to significantly impact the local space environment. However, undesirable effects might be expected to begin building up as the storage regions begin to be filled. After long periods of time, the accumulated displacements of the canisters caused by gravity perturbations of the Earth-Moon-Sun system, solar pressure, atmospheric drag, mass concentrations in the Earth and, possibly, because of mutual gravity attractions, could lead to increased chances of collisions. Also, the long-term stability of objects in orbit about the Earth cannot be assured, e.g., orbital decay and subsequent reentry. Methods of monitoring or systems (orbiting disposal stations) which would reduce the chance for orbital decay and subsequent reentry or collisions of waste canisters should be developed if this option is chosen.

4.3.3.5.2 Heliocentric Trajectories

The launching of nuclear waste canisters into heliocentric trajectories either toward or away from the Sun would be a disposal option rather than a storage option because the waste would be ejected from the Earth sphere-of-influence. For all practical purposes, they could not be recovered.

The destination in the case of the heliocentric orbit disposal option is a region of space encircling the Sun, either outside or inside the Earth's orbit. The propulsion requirements, assuming chemical propulsion, for placing the waste canisters into orbit close to the Sun are too great for practical consideration; however, other propulsion concepts, SSP, SEP, or NEP might be used to obtain orbits less than 0.2 a.u. (1 a.u. = mean Sun-Earth distance, 1.50×10^8 km). The closer the orbit to the Sun, the less chance there is for future Earth encounter as a result of orbit shifts due to orbital perturbations. Heliocentric orbits out from the Earth should be far enough that future Earth encounters are considered improbable. Impacts to space of disposal in regions nearer to the Earth but far enough out to preclude Earth encounter, would not present an orbital debris problem for future space flights (probability of encounters with other spacecraft are extremely low).

The possibility of failure of a canister in heliocentric orbit is extremely remote. However, if a canister should rupture, for example, as a result of a meteor impact or because of long-term degradation of the canister wall, then the contents could be released and begin to spread, threatening to eventually fall back onto Earth or onto another planet. The physical processes by which the nuclear waste material would be transported in heliocentric space include sputtering, thermal diffusion, and interactions with solar radiation and wind. Large pieces or particles of waste material would be sputtered into smaller particles which in turn would spread by diffusion. The smallest particles, with radii less than 10^{-5} to 10^{-4} cm, would be swept out of the solar system directly by solar radiation pressure. Larger particles, those with radii up to 10^{-3} to 10^{-2} cm, would gradually lose momentum through scattering, charge exchange interactions and collisions with energetic photons and solar wind protons. This process, called the Poynting-Robertson effect, would cause the large particles to begin moving in toward the Sun where eventually they would be vaporized and broken down into smaller particles. Once this occurs, the smaller particles would then be swept out of the solar system under the influence of the solar radiation pressure. The time period of this sweeping-out process is estimated to be on the order of 10^3 to 10^4 years.[4-44]

In a 1974 environmental assessment for SEPS which dealt with the release of mercury, it was estimated that the mercury would be quickly ionized so that if the release were outside the Earth's magnetosphere, the mercury atoms would be deflected by the Earth's bow shock and no material would reenter the Earth environment.[4-45] The same reasoning would apply to

the case of radioactive waste since some ionization either by photoionization or charge exchange would be expected to occur. Almost all of the physical processes involved would tend to prevent the radioactive waste from falling onto the Earth or another planet. Consequently, very little or no radioactive waste would be expected to fall on the Earth or another planet as a result of release of radioactive waste material in heliocentric space and no adverse effects would be expected. However, further study of this particular problem appears warranted.

4.3.3.5.3 Lunar Surface Storage

The storage of nuclear waste canisters on the surface of the Moon is envisioned to incorporate the following orbital operations: (1) delivery of the waste canisters to low Earth orbit by the Shuttle and subsequent transfer to the OTV, (2) a velocity impulse maneuver to a translunar coast trajectory, (3) a lunar velocity impulse maneuver to place the payload into lunar capture orbit, and (4) final burns to soft land the package and OTV in the landing area on the Moon's surface, perhaps a large crater.

It is assumed that positive measures would be taken to prevent spilling and spreading of nuclear wastes on the lunar surface, that practical measures would be taken to preserve the Moon's pristine condition, and that it would be exceedingly unwise to forfeit any possible future uses or values of the Moon by indiscriminate disposal operations (see Section 4.6 concerning political implications relating to this event). Man may in the future wish to use the Moon as a location for scientific and astronomical bases. Also, as recently suggested by advocates of Space Power Stations (SPS)[4-12] and of space colonies[4-13], the moon could be used in the future as a base for mining operations to support materials requirements of these concepts.

Consequently, uncontrolled, free-fall landings of nuclear waste containers are considered to be unacceptable. The controlled, soft landings are considered essential (OTV employing landing systems similar to the LM of the Apollo Program). It is recommended that to avoid the possibility of landing one OTV canister atop another at the lunar destination site, it would probably be desirable to provide separate landing and storage sites and a surface transport vehicle (automated or manned) to move the canisters and OTVs from the landing site to storage sites. Figure 4-1 illustrates a concept of an established lunar repository for nuclear waste storage. The separation distance between the landing site, the storage site, and "OTV Junk Yard" site would be significantly greater than the cumulative inaccuracies of the OTV's guidance system. The repository could be manned or completely automated. For example, a repository might be operated in conjunction with a lunar mining operation, in which case the waste canisters could be stored in abandoned excavations or in trenches.

The natural environment of the Moon is essentially benign. There is no atmosphere and no free water. Lunar quakes are believed to be weak-to-mild, especially in the maria regions where there are deep layers of dust and crushed rock. Volcanic activity appears to be rare. The only significant threat posed by the natural environment appears to be that of meteorite strikes.

Figure 4-2 shows, for a given lunar area (maria - 10 km^2), the expected number of meteorite impacts during a period of one million years as a function of impact crater diameter.[4-14] It is likely that one meteorite over a one million year period will strike a 10 km^2 region of the Moon and produce a crater about 20 m in diameter. Smaller strikes occur more frequently and larger strikes occur less frequently. The probability of damage as a result of a

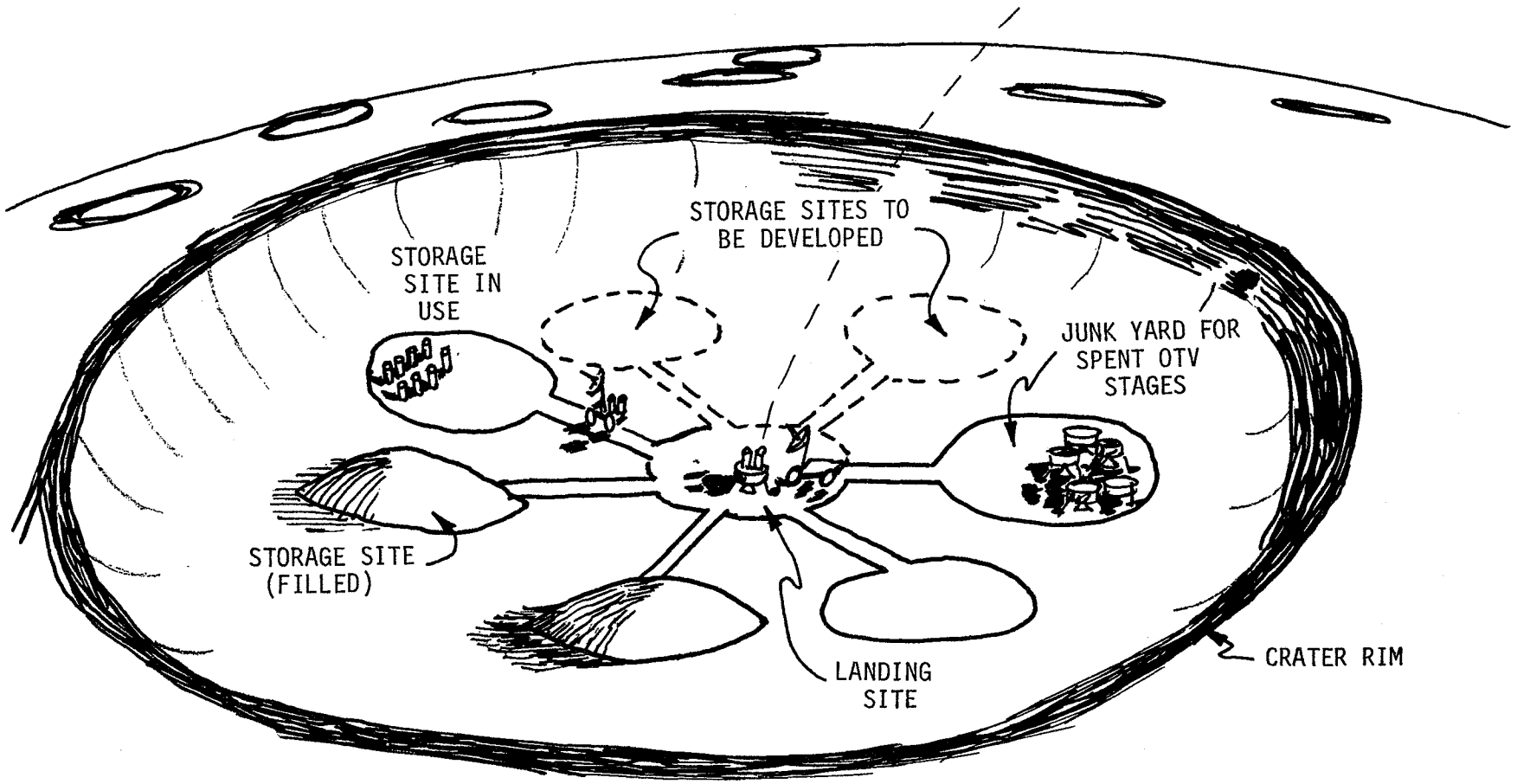


FIGURE 4-1. LUNAR REPOSITORY FOR NUCLEAR WASTE

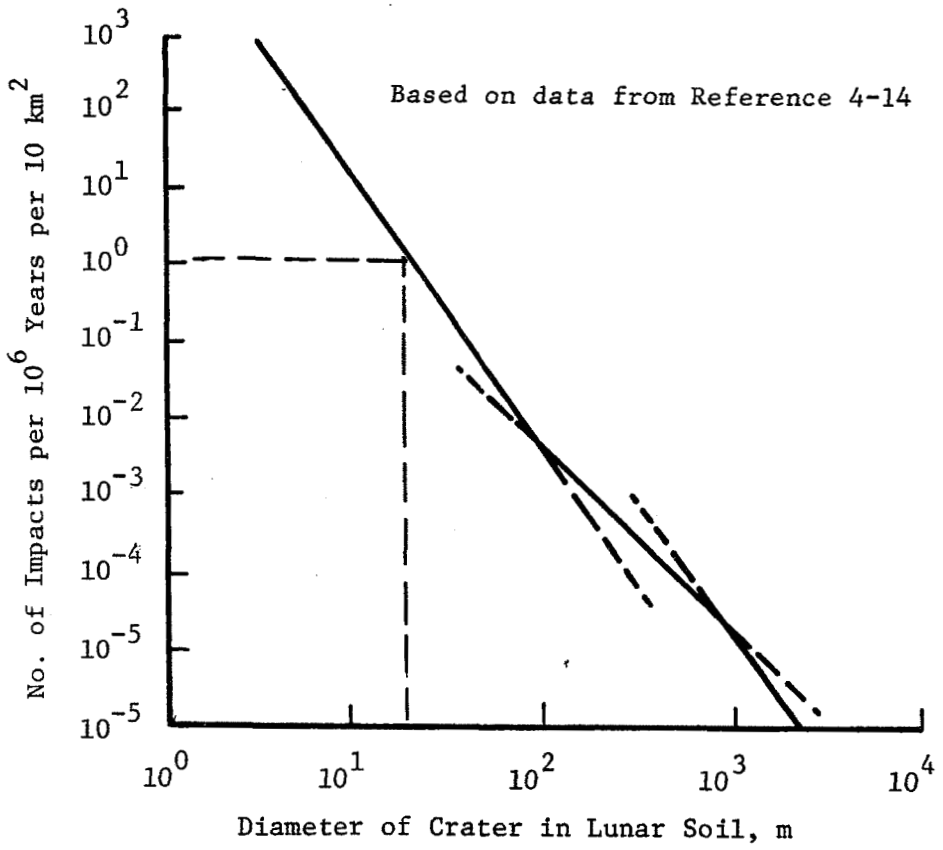


FIGURE 4-2. ESTIMATED NUMBER OF METEORITE IMPACTS AT A LUNAR MARIA SITE (10 km^2) DURING A PERIOD OF 10^6 YEARS

meteorite strike can be reduced by covering the canisters with lunar soil or burying them below the surface. Careful consideration would have to be given to the thermal conductivity of the lunar soil, so as to prevent overheating of the waste canisters.

The solar wind, cosmic rays, and thermal cycling of the natural lunar environment are not expected to constitute as great a threat as meteorite strikes. If the wastes are protected against damage by meteorites, then the other factors will not constitute a threat to a breach of containment.

4.3.3.5.4 Solar System Escape

The normal solar system escape mission would be expected to provide the least environmental impact of any of the options. If the waste canisters were given at least the solar system escape velocity impulse (16.7 km/sec), they would have just enough energy to escape from the solar system. They would exit with zero relative velocity and float along with the solar system just outside its sphere of influence and never return. There, they would be isolated from any predictable or foreseeable detrimental or undesirable interactions.

No impacts to other planetary systems (star systems within our galaxy) would be expected if more than escape velocity were provided to the payload. Targeting could be selected to preclude any interaction for hundreds of millions of years during which time the waste would become harmless.

4.3.3.6 Energy Requirements

The annual energy requirements for materials and propellants for the Space Shuttle operation in support of nuclear waste disposal in space have been calculated based upon data in References 4-6 and 4-15. The results of these calculations for the years 1991 and 2000 are shown in Table 4-4. LH_2/LO_2 propellant requirements for the OTV, not included, are estimated to be only 5 percent of the values shown in the table. Total energy requirements for the launch operations, including mission support and manufacturing activities, are probably a factor of 2 higher in all cases (see Reference 4-15).

Space transportation energy impacts for Mix No. 1 are considered severe, whereas the energy requirements for disposal of the other mixes will have total space transport energy requirements comparable to or less than the current estimate for 60 Shuttle flights per year, 24×10^{12} KJ.[4-6] Total energy requirements for space transport activities associated with the disposal of Mix No. 1, in the year 2000, is estimated to be roughly half of the total electrical energy generated by the 380 GWe capacity of nuclear reactors in the U.S. in that same year. Again, this estimate, while only a rough approximation does clearly indicate that space disposal of waste Mix No. 1 is not practical. Other mixes require, for space transport energy, from 0.1 to 3.0 percent of the total U.S. nuclear generating capacity in the year 2000. This is much more reasonable from an energy payback viewpoint.

4.4 Preliminary Environmental Assessment of Abnormal Events

The material discussed in this section relates to the evaluation of various worst-case abnormal events, where abnormal events are defined as those events which are postulated (may not be credible) to occur as a result of an accident or an intrusive act of man (see Section 4.7).

TABLE 4-4. ENERGY REQUIREMENTS FOR SPACE SHUTTLE MATERIALS AND PROPELLANTS REQUIRED TO SUPPORT A NUCLEAR WASTE DISPOSAL PROGRAM

Nuclear Waste Mix Number	Annual Energy Requirement for Space Shuttle Materials and Propellants 10^{12} kJ	
	CY-1991	CY-2000
1	150	420
2	8	19
3	6	16
4	3	6
5	1	1

The analysis worst-case abnormal events may suggest changes in system design or operation which would ultimately reduce the risk to man.

Abnormal events possible during the operation of a space-based nuclear waste disposal program are outlined in Table 4-1. Abnormal events related to post-reactor processing and terrestrial transportation of the nuclear waste and other radioactive materials within the United States have been or are being studied.[4-1 through 4-5 and 4-16 through 4-21] The effects related to Space Shuttle launch abnormal events (no consideration of payload) have been addressed in Reference 4-6. In concert with the scope of the present study, only the most severe abnormal events associated with the release of radioactive material during space operations will be examined here (priority one study areas). No attempt has been made to determine the credibility of these events.

The many space disposal options that are currently under consideration by NASA/MSFC are outlined in Section 1. All of these space disposal options pose similar worst-case accident potential to the Earth. All require the launch of a nuclear waste payload by the Space Shuttle from a launch site on the Earth's surface. All options require the use of an orbit transfer vehicle (OTV) to deliver the nuclear waste payload to the desired space destination. Worst-case accidents are assumed to result in the release of all of the radioactive waste (~5500kg) into the lower atmosphere, upper atmosphere, into the oceans or fresh water lakes, and onto the land. All such releases can subsequently affect man and his Earth's ecosystems to various degrees. The abnormal events studied here are as follows:

- On or near pad catastrophic launch vehicle explosion and fire (major impact to lower atmosphere)
- Launch vehicle explosion and fire at high altitude or reentry and burnup of the nuclear waste payload from orbit (major impact to upper atmosphere—followed by chronic impact to lower atmosphere)
- Water impact resulting from launch vehicle failure or intact reentry of the nuclear waste payload from orbit (major impact to ocean or fresh water)
- Land impact resulting from launch vehicle failure or intact reentry of the nuclear waste payload (major impact to land).

Evaluation of these four types of accidents will provide initial information necessary to begin weighing the risk to man versus: design of the cocoon and container; the choice of waste form and the mix; and the establishment of operational plans and procedures.

Effects from accidents in space vary according to the space disposal option considered. Accidents in space can result in the release of long-lived radioactive material into various orbits and onto various celestial bodies. Evaluation of these accidents should provide information necessary to weigh the risk of space contamination versus: design of the container and OTV; the choice of the waste form and mix; and the establishment of operational plans and procedures.

The calculation of the probabilities of the postulated abnormal events caused by accidents and intrusive acts of man are beyond the scope of this study. Future study efforts will be required to develop this information. The occurrence probabilities of worst-case abnormal events postulated here are believed to be extremely small.

The baseline assumptions used in the evaluation of the five areas of abnormal events involving the release of all of the nuclear waste payload are as follows:

- Mix No. 3
- Calcine powder waste form
- 5500 kg nuclear waste payload
- Space Shuttle launch vehicle
- Hydrogen/oxygen OTV
- KSC or remote Atlantic Ocean island launch site
- Worst-case scenarios assumed.

When it is appropriate, variations to the baseline assumptions are called out and treated accordingly.

The following subsections are organized as follows. Each abnormal event is discussed. Impacts to air, water and land quality are then briefly analyzed where appropriate. Then factors which must be defined to determine the risk of ecosystem and human health and safety effects are briefly discussed.

4.4.1 On or Near Pad Catastrophic Launch Vehicle Explosion and Fire with the Release of Radioactive Material

A major failure of the launch vehicle on or near the pad could conceivably cause the rupture of the cocoon and container holding the nuclear waste payload. Basically, three types of events have been postulated. In all three, loss of life would at least involve members of the Space Shuttle crew. The first would be an on pad event involving a catastrophic explosion and fire (also includes vehicle fall back on the pad). A failure of a major launch vehicle system element such as failure of one SRM to ignite, SRM case failure, Space Shuttle main engine (SSME) system failure, External Tank (ET) structural failure, premature initiation of the ET destruct system, or a major failure in the control of the vehicle, could cause this type of event. The second event would be a system failure which occurs while the vehicle is still near the launch pad area (less than 5 km in altitude). The event would be an explosion and fire in the upper regions of the lower atmosphere (troposphere). The third event would be a guidance and/or control system failure where the vehicle would tip over and strike the ground resulting in an explosion and fire. For all three of these events, one can assume that the underlying cause results from human error or an intrusive act.

The worst possible environment for the cocoon would probably be the third event described. The impact velocity of the vehicle coupled with the large amount of propellants available* would provide the most intense thermal and mechanical environments.

Two scenarios have been developed to bound the problem of the worst-case event. In the first scenario, it was assumed that all of the nuclear waste material would be released from the cocoon/container and be distributed as 0.6 μ sized particles in the resulting exhaust cloud (provides worst lung burden—see Figure 4-11). This scenario provides an estimate for worst-case effects on the local human population (external and internal radiation exposure). In the

*Note initial on board major propellant quantities are:
Liquid hydrogen—103,000 kg (226,000 lb)
Liquid oxygen—610,000 kg (1,344,000 lb)
PBAN composite solid propellant—1,008,000 kg (2,220,000 lb).

second scenario, it was assumed that the nuclear waste material is characterized by larger sized particles, such that the particles are driven up into the exhaust cloud and then fall out evenly over an area (10 or 100 km^2) downwind from the launch area. This scenario provides preliminary information necessary to define the range of impacts to local soils, vegetation, animals, and humans.

4.4.1.1 Air Quality

The air quality impacts presented here include only the prediction of downwind concentration and time integrated exposures of airborne radioactive material from a release of 5500 kg (12,125 lb) of nuclear waste as a result of an on or near pad Space Shuttle catastrophic explosion and fire. Other air quality impacts at ground level related to this catastrophic event (e.g., release of HCl, Al_2O_3, Cl_2 and etc.) are expected to be similar or less than those of Space Shuttle normal launches.[4-6]

Model 3 of the NASA/MSFC Multilayer Diffusion Program [4-22] was used to predict the maximum downwind concentrations and time integrated exposures of radioactive material resulting from a catastrophic Space Shuttle failure (slow burn mode). Model 3 was chosen because of its extensive use at NASA/KSC in predicting downwind concentrations and time integrated exposures of HCl and other constituents resulting from the launch of Titan and Delta space vehicles, and its relatively good agreement with measurements. The reader is referred to Reference 4-22 for details concerning the diffusion model. The model employs data such as the temperature, pressure, relative humidity, and wind speed profiles, and the heat release rate to establish the height to which the resulting exhaust could rise.

Three typical meteorological conditions for Kennedy Space Center, Florida were used in the calculations. Figures 4-3 and 4-4 show the maximum ground level concentrations of waste in $\mu g/m^3$ and the maximum ground level time integrated exposures (doses) in $\mu g\ sec/m^3$ as a function of distance from the launch pad for the sea breeze, fall and spring meteorological conditions.* The spring case provides the highest concentration and dosages of radioactive material at distances beyond KSC's boundaries. Table 4-5 provides concentration and exposure data for the spring case.

The ORIGEN computer code was used to produce nuclide data based upon the following assumptions: (1) a burn-up of 33,000 MWD/MT, (2) the waste was 10.5 years out of the reactor, and (3) only LWR's were considered. A list containing the most hazardous twenty-five radioactive nuclides was compiled from the code's output and ranked (higher in list—higher hazard) based upon a Mix No. 3 composition and the ratio of the activity to the maximum permissible concentration (NRC standard) for a given isotope, as given in Reference 4-23. The amounts and fractions of each nuclide in the waste (calcine waste form) for each of the five mixes are shown in Table 4-6. The concentration and exposure of a given nuclide at various distances downwind from the launch pad, can be obtained by multiplying the nuclide fraction (from Table 4-6) by the concentration or exposure data from Figures 4-3 and 4-4. Table 4-7 provides the maximum concentration and exposure data (in terms of nuclide mass and activity) for the hazardous nuclides contained in the five mixes for the spring meteorological case.

*It should be noted that other meteorological conditions can exist at the time of launch which may produce both higher and lower values thun those that are shown in these two figures. Future study should allow a more in-depth analysis of the problem.

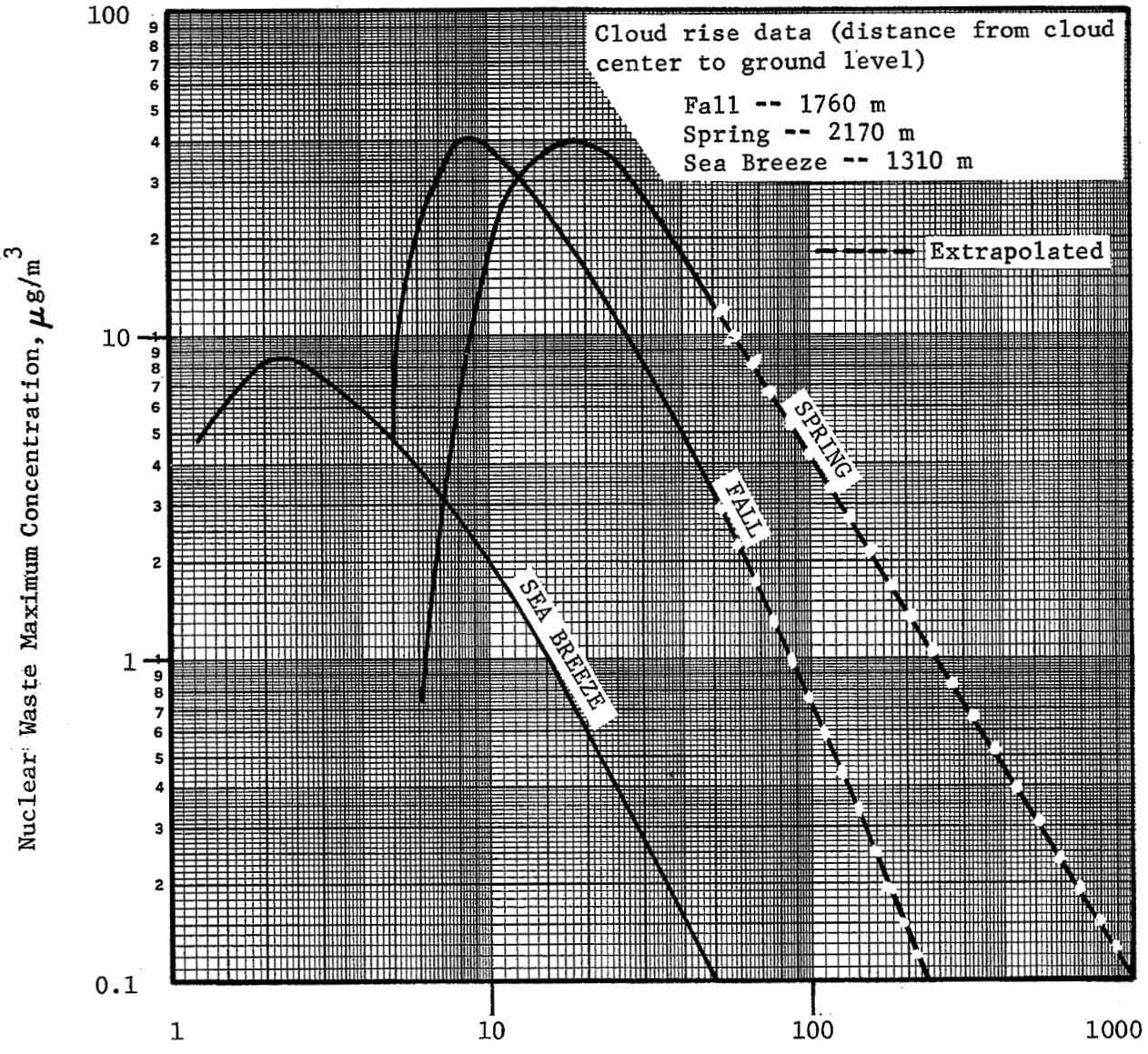


FIGURE 4-3. MAXIMUM DOWNWIND CONCENTRATION OF NUCLEAR WASTE RESULTING FROM A WORST-CASE ON OR NEAR PAD CATASTROPHIC LAUNCH VEHICLE FIRE AND EXPLOSION

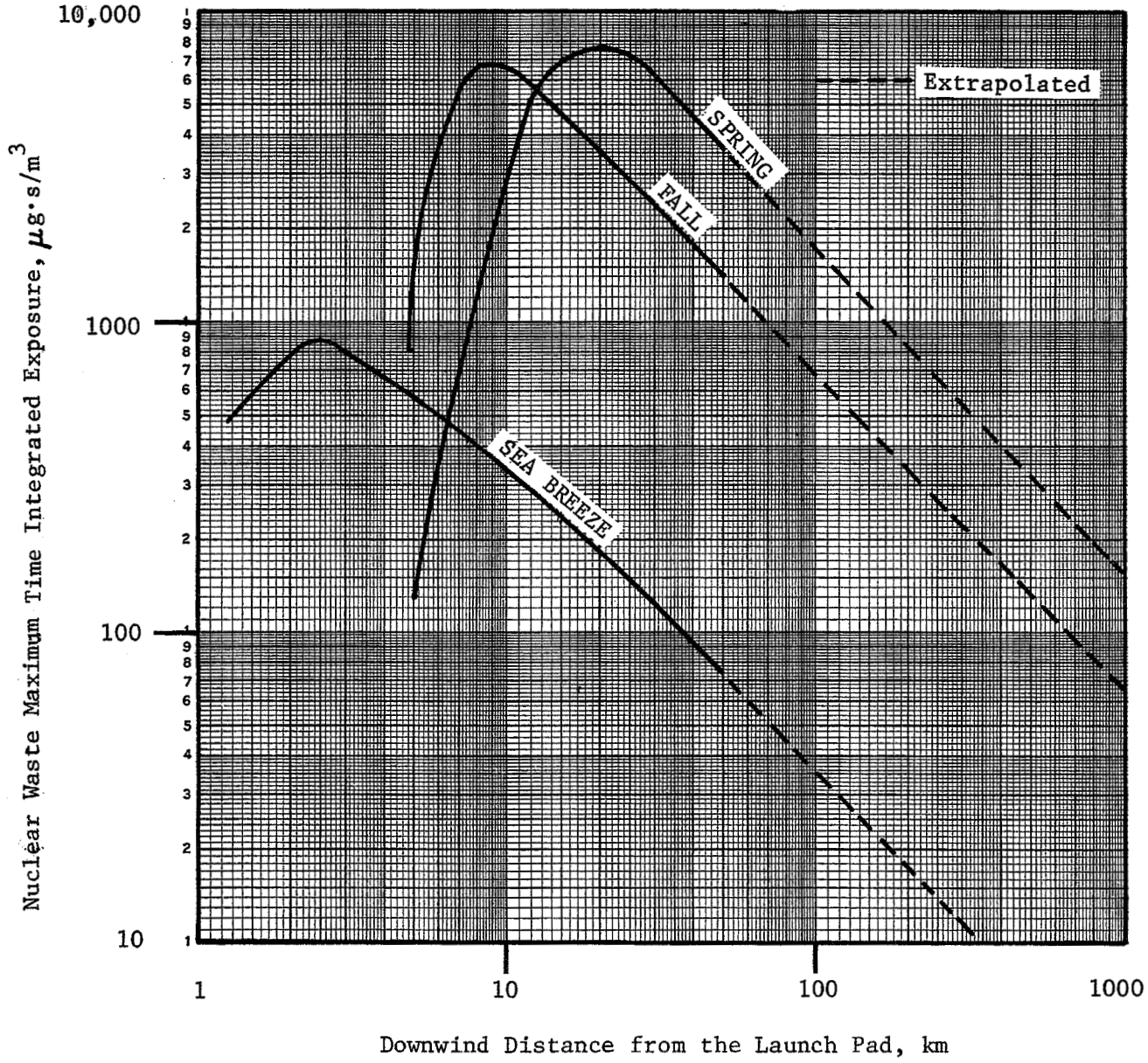


FIGURE 4-4. MAXIMUM DOWNWIND NUCLEAR WASTE TIME INTEGRATED EXPOSURE RESULTING FROM A WORST-CASE ON OR NEAR PAD CATASTROPHIC LAUNCH VEHICLE FIRE AND EXPLOSION

TABLE 4-5. NUCLEAR WASTE CONCENTRATION AND EXPOSURE DATA FOR SPRING METEOROLOGICAL CONDITIONS, AT KSC

Distance, km	Maximum Peak Concentration, $\mu g/m^3$	Maximum Time Integrated Exposure, $\mu g \cdot s/m^3$
5	0.0359	5.3
7.5	3.93	699
10	17.2	3083
15	37.4	6925
18.75	40.0	7668
20	39.6	7687
25	34.4	7050
30	28.0	6109
35	22.5	5247
40	18.3	4564
45	15.1	4025
50	12.6	3602

TABLE 4-6. MASS DISTRIBUTIONS FOR 25 HAZARDOUS NUCLIDES AS A FUNCTION OF WASTE MIX

NUCLIDE		Mix 1		Mix 2		Mix 3		Mix 4		Mix 5	
		kg	fraction	kg	fraction	kg	fraction	kg	fraction	kg	fraction
Curium	244	0.127	2.13×10^{-5}	2.33	4.24×10^{-4}	3.02	5.49×10^{-4}	8.86	1.61×10^{-3}	0	0
Strontium	90	1.93	3.51×10^{-4}	38.3	6.97×10^{-3}	49.7	9.04×10^{-3}	0	0	0	0
Plutonium	238	5.34	9.70×10^{-4}	106.	1.93×10^{-2}	0.687	1.25×10^{-4}	0.402	7.30×10^{-5}	0	0
Americium	241	0.250	4.54×10^{-5}	4.97	9.03×10^{-4}	6.44	1.17×10^{-3}	18.9	3.43×10^{-3}	0	0
Cesium	137	4.55	8.27×10^{-4}	90.2	1.64×10^{-2}	117.	2.13×10^{-2}	343.	6.24×10^{-2}	0	0
Plutonium	241	3.06	5.57×10^{-4}	61.1	1.11×10^{-2}	0.395	7.18×10^{-5}	0.233	4.23×10^{-5}	0	0
Americium	243	0.518	9.42×10^{-5}	10.3	1.87×10^{-3}	13.4	2.43×10^{-3}	39.1	7.11×10^{-3}	0	0
Plutonium	240	21.1	3.84×10^{-3}	420.	7.63×10^{-2}	2.72	4.95×10^{-4}	1.60	2.90×10^{-4}	0	0
Europium	154	0.150	2.72×10^{-5}	2.97	5.40×10^{-4}	3.85	7.00×10^{-4}	11.3	2.05×10^{-3}	0	0
Plutonium	239	24.6	4.48×10^{-3}	490.	8.91×10^{-2}	3.18	5.78×10^{-4}	1.86	3.38×10^{-4}	0	0
Neptunium	237	2.22	4.04×10^{-4}	44.2	8.04×10^{-3}	57.2	1.04×10^{-2}	168.	3.05×10^{-2}	0	0
Curium	245	0.012	2.10×10^{-6}	0.229	4.17×10^{-5}	0.297	5.40×10^{-5}	0.869	1.58×10^{-4}	0	0
Samarium	151	0.196	3.57×10^{-5}	3.91	7.11×10^{-4}	5.07	9.21×10^{-4}	14.8	2.70×10^{-3}	0	0
Curium	246	0.0014	2.58×10^{-7}	0.028	5.13×10^{-6}	0.037	6.65×10^{-6}	0.107	1.95×10^{-5}	0	0
Plutonium	242	1.85	3.36×10^{-4}	36.8	6.69×10^{-3}	0.238	4.33×10^{-5}	0.140	2.54×10^{-5}	0	0
Technetium	99	3.93	7.14×10^{-4}	78.1	1.42×10^{-2}	101.	1.84×10^{-2}	0	0	2547	4.63×10^{-1}
Tin	126	0.094	1.71×10^{-5}	1.86	3.39×10^{-4}	2.42	4.40×10^{-4}	0	0	0	0
Selenium	79	0.026	4.81×10^{-6}	0.526	9.57×10^{-5}	0.682	1.24×10^{-4}	0	0	0	0
Uranium	234	0.524	9.53×10^{-5}	0.052	9.47×10^{-6}	0.068	1.23×10^{-5}	0.039	7.17×10^{-6}	0	0
Zirconium	93	3.39	6.17×10^{-4}	67.7	1.23×10^{-2}	87.5	1.59×10^{-2}	0	0	0	0
Uranium	238	4405.	8.01×10^{-1}	438.	7.97×10^{-2}	566.	1.03×10^{-1}	333.	6.05×10^{-2}	0	0
Uranium	236	2.00	3.63×10^{-4}	0.199	3.61×10^{-5}	0.257	4.68×10^{-5}	0.151	2.74×10^{-5}	0	0
Palladium	107	1.15	2.09×10^{-4}	22.8	4.15×10^{-3}	29.6	5.38×10^{-3}	0	0	0	0
Cesium	135	1.46	2.65×10^{-4}	29.0	5.27×10^{-3}	37.6	6.83×10^{-3}	110.	2.00×10^{-2}	0	0
Uranium	235	3.16	5.74×10^{-4}	0.314	5.71×10^{-5}	0.407	7.40×10^{-5}	0.238	4.33×10^{-5}	0	0
Total		4487.	8.16×10^{-1}	1950.	3.55×10^{-1}	1089.	1.98×10^{-1}	1051.	1.91×10^{-1}	2547	4.63×10^{-1}
Other Nuclides and Oxygen		1013.	1.84×10^{-1}	3262.	4.07×10^{-1}	4037.	7.34×10^{-1}	3920.	7.13×10^{-1}	1441	2.62×10^{-1}
Inert Additives		0	0	288.	5.23×10^{-2}	374	6.78×10^{-2}	529.	9.61×10^{-2}	1512	2.75×10^{-1}
TOTAL		5500.	1.0	5500.	1.0	5500.	1.0	5500.	1.0	5500.	1.0

4.4.1.2 Water Quality

The worst-case impact to water quality as a result of an on or near pad catastrophic failure of launch vehicle carrying a payload of nuclear waste material would be from a totally ruptured container where all the radioactive material would be released and distributed over a body of water downwind from the pad. This impact is very similar to the land quantity impact to be discussed in Section 4.4.1.3, except the radioactive material deposited on the surface of water would eventually dissolve and residuals, if any, would settle down to the bottom.

For this preliminary analysis, the approach taken in Section 4.4.1.3 (Land Quality) will be adopted here for the water quality assessment. That is, the radioactive material would be assumed to be uniformly distributed over areas of 10 and 100 km^2; but in the case of water, this material is dissolved uniformly in water to any chosen depth. The surface distribution is given in Table 4-8 in terms of $\mu g/m^2$ and $\mu Ci/m^2$ for 10 km^2 area. These figures can be converted to concentrations in μg or μCi per cubic meter by dividing them by any depth value (meters). If the area of distribution is 100 km^2, the concentration could be obtained by dividing those numbers by 10. For example, if the depth of dissolution is 50 m, the concentration of curium 244 from Mix No. 3 would be 6 $\mu g/m^3$ or 500 $\mu Ci/m^3$ for 10 km^2 area and 0.6 $\mu g/m^3$ or 50 $\mu Ci/m^3$ for 100 km^2.

4.4.1.3 Land Quality

The worst-case impact to land quality as a result of a catastrophic on or near pad launch vehicle failure would occur if all of the radioactive material contained in the nuclear waste payload (5500 kg) were distributed over a land area downwind from the launch pad. It was assumed that the radioactive material containment vessel would be ruptured and all of the material would be released. The particle size would be greater than that assumed in Section 4.4.1.1—Air Quality, such that fallout would be dominant. The environment resulting from the explosion and combustion of launch vehicle propellant would likely drive the radioactive particles up into the air along with the hot exhaust products from the propellant combustion. For this preliminary analysis it was assumed that the radioactive material would be uniformly distributed over both 10 and 100 km^2 areas. Table 4-8 presents ground distribution data for the twenty-five hazardous nuclides that exist in Mix No. 3. Data in the table are shown for an even distribution over a 10 km^2 area; to obtain data for the 100 km^2 area, divide by a factor of 10.

4.4.1.4 Ecosystem Effects

The effect of an on or near pad catastrophic LV failure with release of radioactive material must consider the zone from 100 m above the soil surface (including all biota migrating within the area) to the ground-water aquifers. Aquatic systems are defined as surface and subsurface portions, including those flowing within sediments to depths of 10 m. Aquifers lying beneath sediments will be ignored in this analysis because not enough information is available to include them and the probability of their significance for this analysis is negligible.

Ecosystem effects which could be attributable to the catastrophic event include: (1) acute toxicity causing death, somatic damage, or reproductive damage, e.g., mutagenesis; (2) sublethal toxicity which chronically causes losses in tissue, organ, organismic, population, or community productivity; (3) bioaccumulation to toxic thresholds; and (4) disruption of vital ecosystem processes, such us nutrient cycling. The ability to discern the effects of a

TABLE 4-7. MAXIMUM CONCENTRATION AND TIME INTEGRATED EXPOSURES AT 20 KM DOWNWIND FROM PAD FOR VARIOUS NUCLEAR WASTE MIX OPTIONS RESULTING FROM AN ON OR NEAR PAD CATASTROPHIC SPACE SHUTTLE FAILURE*

		Mix No. 1				Mix No. 2				Mix No. 3				Mix No. 4			
		Concentration		Time Integrated Exposure		Concentration		Time Integrated Exposure		Concentration		Time Integrated Exposure		Concentration		Time Integrated Exposure	
Nuclide		$\mu g/m^3$	$\mu Ci/m^3$	$\mu g \cdot s/m^3$	$\mu Ci \cdot s/m^3$	$\mu g/m^3$	$\mu Ci/m^3$	$\mu g \cdot s/m^3$	$\mu Ci \cdot s/m^3$	$\mu g/m^3$	$\mu Ci/m^3$	$\mu g \cdot s/m^3$	$\mu Ci \cdot s/m^3$	$\mu g/m^3$	$\mu Ci/m^3$	$\mu g \cdot s/m^3$	$\mu Ci \cdot s/m^3$
Curium	244	$8.4x10^{-4}$	$7.0x10^{-2}$	$1.6x10^{-1}$	$1.3x10^{+1}$	$1.7x10^{-2}$	$1.4x10^{0}$	$3.3x10^{0}$	$2.7x10^{2}$	$2.2x10^{-2}$	$1.8x10^{0}$	$4.3x10^{0}$	$3.6x10^{2}$	$6.4x10^{-2}$	$5.3x10^{0}$	$1.2x10^{+1}$	$9.9x10^{2}$
Strontium	90	$1.4x10^{-2}$	$2.0x10^{0}$	$2.7x10^{0}$	$3.9x10^{+2}$	$2.8x10^{-1}$	$4.0x10^{1}$	$5.4x10^{+1}$	$7.8x10^{3}$	$3.6x10^{-1}$	$5.2x10^{1}$	$7.0x10^{+1}$	$1.0x10^{4}$	0	0	0	0
Plutonium	238	$3.8x10^{-2}$	$6.6x10^{-1}$	$7.4x10^{0}$	$1.3x10^{2}$	$7.6x10^{-1}$	$1.3x10^{1}$	$1.5x10^{+2}$	$2.6x10^{3}$	$5.0x10^{-3}$	$8.7x10^{-2}$	$9.7x10^{-1}$	$1.7x10^{1}$	$2.9x10^{-3}$	$5.0x10^{-2}$	$5.6x10^{-1}$	$9.7x10^{0}$
Americium	241	$1.8x10^{-3}$	$5.8x10^{-3}$	$3.5x10^{-1}$	$1.1x10^{0}$	$3.6x10^{-2}$	$1.2x10^{-1}$	$7.0x10^{0}$	$2.3x10^{1}$	$4.6x10^{-2}$	$1.5x10^{-1}$	$8.9x10^{0}$	$2.9x10^{1}$	$1.4x10^{-1}$	$4.5x10^{-1}$	$2.7x10^{+1}$	$8.7x10^{1}$
Cesium	137	$3.3x10^{-2}$	$3.3x10^{0}$	$6.4x10^{0}$	$6.3x10^{2}$	$6.5x10^{-1}$	$6.4x10^{1}$	$1.3x10^{+2}$	$1.3x10^{4}$	$8.4x10^{-1}$	$8.3x10^{1}$	$1.6x10^{+2}$	$1.6x10^{4}$	$2.5x10^{0}$	$2.5x10^{2}$	$4.9x10^{+2}$	$4.8x10^{4}$
Plutonium	241	$2.2x10^{-2}$	$2.5x10^{0}$	$4.3x10^{0}$	$4.9x10^{2}$	$4.4x10^{-1}$	$5.0x10^{1}$	$8.5x10^{+1}$	$9.6x10^{3}$	$2.8x10^{-3}$	$3.2x10^{-1}$	$5.4x10^{-1}$	$6.1x10^{1}$	$1.7x10^{-3}$	$1.9x10^{-1}$	$3.3x10^{-1}$	$3.7x10^{1}$
Americium	243	$3.7x10^{-3}$	$6.8x10^{-4}$	$7.2x10^{-1}$	$1.3x10^{-1}$	$7.4x10^{-2}$	$1.4x10^{-2}$	$1.4x10^{+1}$	$2.6x10^{0}$	$9.6x10^{-2}$	$1.7x10^{-2}$	$1.9x10^{+1}$	$3.5x10^{0}$	$2.8x10^{-1}$	$5.2x10^{-2}$	$5.4x10^{+1}$	$9.9x10^{0}$
Plutonium	240	$1.5x10^{-1}$	$3.4x10^{-2}$	$2.9x10^{+1}$	$6.6x10^{-2}$	$3.0x10^{0}$	$6.8x10^{-1}$	$5.8x10^{+2}$	$1.3x10^{2}$	$2.0x10^{-2}$	$6.3x10^{-3}$	$3.9x10^{0}$	$8.9x10^{-1}$	$1.1x10^{-2}$	$2.5x10^{-3}$	$2.1x10^{0}$	$4.8x10^{-1}$
Europium	154	$1.1x10^{-3}$	$1.6x10^{-1}$	$2.1x10^{-1}$	$3.0x10^{1}$	$2.1x10^{-2}$	$3.0x10^{0}$	$4.1x10^{0}$	$5.9x10^{2}$	$2.8x10^{-2}$	$4.1x10^{0}$	$5.4x10^{0}$	$7.8x10^{2}$	$8.1x10^{-2}$	$1.2x10^{1}$	$1.6x10^{+1}$	$2.3x10^{3}$
Plutonium	239	$1.8x10^{-1}$	$1.1x10^{-2}$	$3.5x10^{+1}$	$2.2x10^{0}$	$3.5x10^{0}$	$2.2x10^{-1}$	$6.8x10^{+2}$	$4.2x10^{1}$	$2.3x10^{-2}$	$1.4x10^{-3}$	$4.5x10^{0}$	$2.8x10^{-1}$	$1.3x10^{-2}$	$8.0x10^{-4}$	$2.5x10^{0}$	$1.5x10^{-1}$
Neptunium	237	$1.6x10^{-2}$	$1.1x10^{-5}$	$3.1x10^{0}$	$2.1x10^{-3}$	$3.2x10^{-1}$	$2.2x10^{-4}$	$6.2x10^{+1}$	$4.2x10^{-2}$	$4.1x10^{-1}$	$2.8x10^{-4}$	$8.0x10^{+1}$	$5.5x10^{-2}$	$1.2x10^{0}$	$8.3x10^{-4}$	$2.3x10^{+2}$	$1.6x10^{-1}$
Curium	245	$8.3x10^{-5}$	$1.3x10^{-5}$	$1.6x10^{-2}$	$2.6x10^{-3}$	$1.7x10^{-3}$	$2.7x10^{-4}$	$3.3x10^{-1}$	$5.3x10^{-2}$	$2.1x10^{-3}$	$3.4x10^{-4}$	$4.1x10^{-1}$	$6.6x10^{-2}$	$6.3x10^{-3}$	$1.0x10^{-3}$	$1.2x10^{0}$	$1.9x10^{-1}$
Samarium	151	$1.4x10^{-3}$	$3.8x10^{-2}$	$2.7x10^{-1}$	$7.3x10^{0}$	$2.8x10^{-2}$	$7.6x10^{-1}$	$5.4x10^{0}$	$1.5x10^{2}$	$3.6x10^{-2}$	$9.8x10^{-1}$	$7.0x10^{0}$	$1.9x10^{2}$	$1.1x10^{-1}$	$2.9x10^{0}$	$2.1x10^{+1}$	$5.7x10^{2}$
Curium	246	$1.0x10^{-5}$	$2.7x10^{-6}$	$1.9x10^{-3}$	$5.0x10^{-4}$	$2.0x10^{-4}$	$5.3x10^{-5}$	$3.9x10^{-2}$	$1.0x10^{-2}$	$2.6x10^{-4}$	$6.9x10^{-5}$	$5.0x10^{-2}$	$1.3x10^{-2}$	$7.7x10^{-4}$	$2.0x10^{-4}$	$1.5x10^{-1}$	$3.9x10^{-2}$
Plutonium	242	$1.3x10^{-2}$	$5.1x10^{-5}$	$2.5x10^{0}$	$9.8x10^{-3}$	$2.6x10^{-1}$	$1.0x10^{-3}$	$5.0x10^{+1}$	$2.0x10^{-1}$	$1.7x10^{-3}$	$6.6x10^{-6}$	$3.3x10^{-1}$	$1.3x10^{-3}$	$1.0x10^{-3}$	$3.9x10^{-6}$	$1.9x10^{-1}$	$7.4x10^{-4}$
Technetium	99	$2.8x10^{-2}$	$4.8x10^{-4}$	$5.4x10^{0}$	$9.2x10^{-2}$	$5.6x10^{-1}$	$9.6x10^{-3}$	$1.1x10^{+2}$	$1.9x10^{0}$	$7.3x10^{-1}$	$1.2x10^{-2}$	$1.4x10^{+2}$	$2.4x10^{0}$	0	0	0	0
Tin	126	$6.8x10^{-4}$	$1.9x10^{-5}$	$1.3x10^{-1}$	$3.6x10^{-3}$	$1.3x10^{-2}$	$3.6x10^{-4}$	$2.5x10^{0}$	$7.0x10^{-2}$	$1.7x10^{-2}$	$4.8x10^{-4}$	$3.3x10^{0}$	$9.2x10^{-2}$	0	0	0	0
Selenium	79	$1.9x10^{-4}$	$1.3x10^{-5}$	$3.7x10^{-2}$	$2.6x10^{-3}$	$3.8x10^{-3}$	$2.7x10^{-4}$	$7.4x10^{-1}$	$5.2x10^{-2}$	$4.9x10^{-3}$	$3.4x10^{-4}$	$9.5x10^{-1}$	$6.7x10^{-2}$	0	0	0	0
Uranium	234	$3.8x10^{-3}$	$2.4x10^{-5}$	$7.4x10^{-1}$	$4.6x10^{-3}$	$3.8x10^{-4}$	$2.4x10^{-6}$	$7.4x10^{-2}$	$4.6x10^{-4}$	$4.9x10^{-4}$	$3.0x10^{-6}$	$9.5x10^{-2}$	$5.9x10^{-4}$	$2.8x10^{-4}$	$1.7x10^{-6}$	$5.4x10^{-2}$	$3.3x10^{-4}$
Zirconium	93	$2.4x10^{-2}$	$6.2x10^{-5}$	$4.7x10^{0}$	$1.2x10^{-2}$	$4.9x10^{-1}$	$1.3x10^{-3}$	$9.5x10^{+1}$	$2.5x10^{-1}$	$6.3x10^{-1}$	$1.6x10^{-3}$	$1.2x10^{+2}$	$3.1x10^{-1}$	0	0	0	0
Uranium	238	$3.2x10^{+1}$	$1.1x10^{-5}$	$6.2x10^{+3}$	$2.1x10^{-3}$	$3.2x10^{0}$	$1.1x10^{-6}$	$6.2x10^{+2}$	$2.1x10^{-4}$	$4.1x10^{0}$	$1.4x10^{-6}$	$8.0x10^{+2}$	$2.7x10^{-4}$	$2.4x10^{-0}$	$8.0x10^{-7}$	$4.7x10^{+2}$	$1.6x10^{-3}$
Uranium	236	$1.4x10^{-2}$	$8.8x10^{-7}$	$2.7x10^{0}$	$1.7x10^{-4}$	$1.4x10^{-3}$	$5.8x10^{-8}$	$2.7x10^{-1}$	$1.7x10^{-5}$	$1.9x10^{-3}$	$1.2x10^{-7}$	$3.7x10^{-1}$	$2.3x10^{-5}$	$1.1x10^{-3}$	$6.9x10^{-8}$	$2.1x10^{-1}$	$1.3x10^{-5}$
Palladium	107	$8.3x10^{-3}$	$4.0x10^{-6}$	$1.6x10^{0}$	$7.7x10^{-4}$	$1.6x10^{-1}$	$7.7x10^{-5}$	$3.1x10^{+1}$	$1.5x10^{-2}$	$2.1x10^{-1}$	$1.0x10^{-4}$	$4.1x10^{+1}$	$1.9x10^{-2}$	0	0	0	0
Cesium	135	$1.0x10^{-2}$	$8.8x10^{-6}$	$1.9x10^{0}$	$1.7x10^{-3}$	$2.1x10^{-1}$	$1.8x10^{-4}$	$4.1x10^{+1}$	$3.6x10^{-2}$	$2.7x10^{-1}$	$2.4x10^{-4}$	$5.2x10^{+1}$	$4.6x10^{-2}$	$7.9x10^{-1}$	$7.0x10^{-4}$	$1.5x10^{+2}$	$1.3x10^{-1}$
Uranium	235	$2.3x10^{-2}$	$4.9x10^{-8}$	$4.5x10^{0}$	$9.7x10^{-6}$	$2.3x10^{-3}$	$4.9x10^{-9}$	$4.5x10^{-1}$	$9.7x10^{-7}$	$2.9x10^{-3}$	$6.2x10^{-9}$	$5.6x10^{-1}$	$1.2x10^{-6}$	$1.7x10^{-3}$	$3.7x10^{-9}$	$3.3x10^{-1}$	$7.1x10^{-7}$

*Note: For MIX No. 5 - Tc-99 concentration = 18 $\mu g/m^3$ (0.31 $\mu Ci/m^3$)

Tc-99 time integrated exposure = 3560 $\mu g \cdot s/m^3$ (61 $\mu Ci \cdot s/m^3$).

TABLE 4-8. WORST-CASE DISTRIBUTION OF RADIOACTIVE MATERIAL OVER A 10 KM^2 AREA RESULTING FROM ON PAD CATASTROPHIC LV FAILURE

Nuclide		Mix No. 1		Mix No. 2		Mix No. 3		Mix No. 4	
		$\mu g/m^2$	$\mu Ci/m^2$	$\mu g/m^2$	$\mu Ci/m^2$	$\mu g/m^2$	$\mu Ci/m^2$	$\mu g/m^2$	$\mu Ci/m^2$
Curium	244	12	1,000	200	17,000	300	25,000	900	75,000
Strontium	90	190	27,000	3,800	547,000	5,000	720,000	0	0
Plutonium	238	530	9,200	11,000	191,000	69	1,200	40	700
Americium	241	25	80	500	1,600	640	2,100	1,900	6,200
Cesium	137	450	44,000	9,000	887,000	12,000	1,182,000	34,000	3,349,000
Plutonium	241	300	33,900	6,100	689,000	40	4,500	20	2,300
Americium	243	50	9	1,000	200	1,300	240	4,000	700
Plutonium	240	2,100	500	42,000	10,000	300	70	200	50
Europium	154	15	2,200	300	44,000	400	58,000	1,100	160,000
Plutonium	239	2,400	150	49,000	3,000	300	20	200	10
Neptunium	237	220	0.15	4,400	3	6,000	4	17,000	12
Curium	245	1	0.16	20	3	30	5	90	14
Samarium	151	20	500	400	11,000	500	14,000	1,500	408,000
Curium	246	0.14	0.04	3	0.8	4	1	10	3
Plutonium	242	180	700	4,000	16	20	0.08	14	0.05
Technetium	99	390	7	8,000	140	10,000	170	0	0
Tin	126	9	0.30	200	6	200	6	0	0
Selenium	79	3	0.20	50	4	70	5	0	0
Uranium	234	50	0.30	5	0.03	7	0.04	4	0.02
Zirconium	93	340	0.90	7,000	18	9,000	23	0	0
Uranium	238	441,000	0.15	44,000	0.01	57,000	0.02	33,000	0.01
Uranium	236	200	0.01	20	0.001	25	0.002	15	0.0009
Palladium	107	115	0.06	2,300	1	3,000	1	0	0
Cesium	135	140	0.12	3,000	3	4,000	4	11,000	10
Uranium	235	300	0.0006	30	0.00006	40	0.00009	20	0.00004

Notes: (a) For MIX No. 5, Tc 99, = 250,000 $\mu g/m^2$ or 4,400 $\mu Ci/m^2$ for 10 km^2 distribution.

(b) For 100 km^2 area divide data in table by 10.

catastrophic on pad event on ecosystems is affected by man's recent alteration of atmospheric (minor), lithospheric (major), and hydrospheric (maximum) processes. Identification of these alterations will be necessary to describe the insult upon ecosystems. The conceptual ecosystem model upon which this analysis is based is shown in Figure 4-5.

Ultimately, one must be able to identify the transport, distribution, and ultimate exposure patterns to the finite numbers of ecosystems in the affected area. The processes which must be considered are: natural phenomena (including meteorological, physical-chemical, and biological) and acts of man. While emphasis in this analysis will be on the former, one cannot assume these phenomena are independent of the latter.

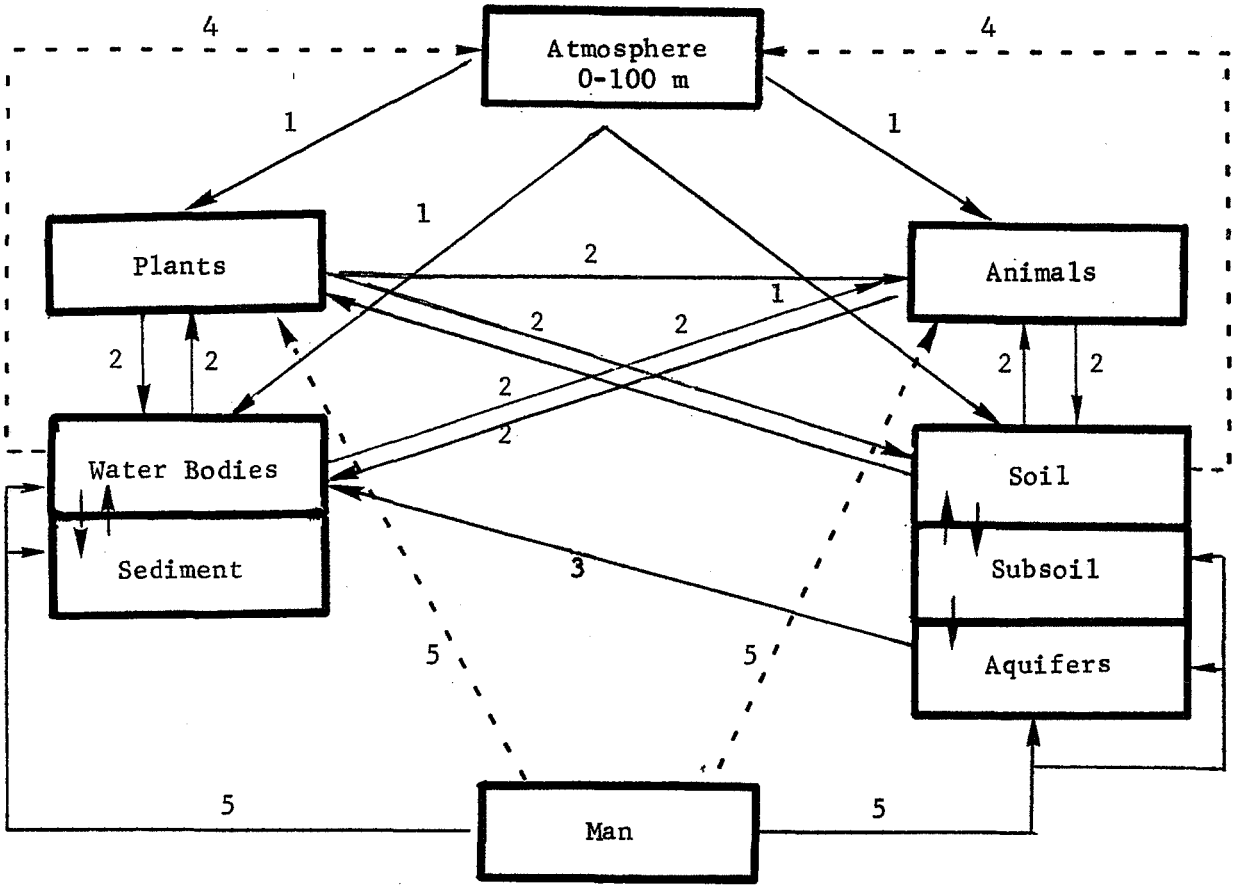
Processes which are dominant in determining the exposure and the resulting effects on ecosystem processes and components are: deposition rates, form and particle size distribution of nuclides, nuclide concentrations, associated wastes or temperature-induced synergisms, local transport rates, interregional transport rates, biomagnification and biologically vectored nuclide form and distribution.

4.4.1.4.1 Acute Toxicity Effects

From the calculations of mass distribution of nuclides present in a catastrophic release on or near the LV pad (see Section 4.4.1.1), the probability is high for acute radiation toxicity to all forms of life within some limited region(see Section 4.4.1.5.1 for predicted exposure data for this event—50 rems/year at 20 km for human lung). Based on studies at the Nevada Test Site, Los Alamos Scientific Laboratory, Oak Ridge National Laboratory and other sites, one would expect death of sensitive populations of the target terrestrial and aquatic ecosystems as a function of the direction of cloud passage and dispersal. Depending upon the exact cloud dispersion pattern, exposures above acute thresholds could occur out to a distance of approximately 100 km, downwind. At this distance, and assuming that the heavier particles have fallen out of the cloud, biota would be affected primarily through inhalation or surface uptake.

Radiation would be significant near regions of high fallout (gravitational settling of heavier particles—yet to be done) for all biota above ground, or on water surfaces, or in air, within very short time intervals. Within regions of high fallout, significant toxic effects would also be expected. Within soil and water columns, acute toxicity would approach an inverse function with depth, modified by the specific percolation rates of the contaminants within the strata. Acute toxicity would decrease with increasing depth since the portion of the biota which have high radiation toxicity thresholds (such as fungi, bacteria, etc.) increases with depth and because dose would decrease with depth.

Acute toxicity can be only superficially compared among the mixes for this analysis. Since at launch a considerable amount of solid and liquid propellants are on board, mortality on the surface area immediately surrounding a catastrophic event caused by fire is expected to be indistinguishable from radiation lethality (see 4.4.1.1). For comparison purposes, the particle size distribution of nuclides in the exhaust cloud produced by the catastrophic event is assumed to be the same for all mixes. Acute toxicity will be approximately the same for Mixes No. 1, No. 2, and No. 3. Mix No. 4 may cause less acute toxicity, especially within soils, sediments, and deeper water bodies due to the omission of highly mobile nuclides strontium-90 and technetium-99. Mix No. 5 has less potential for acute toxicity because of its high dispersion rate in environmental media.



1 Deposition following catastrophic event
2 Transport and ecological exposure pathways
3 Exposure of aquatic systems from contaminated terrestrial systems
4 Resuspension pathways
5 Man affected pathways

FIGURE 4-5. CONCEPTUAL MATRIX OF ROUTES OF POTENTIAL EFFECTS UPON ECOSYSTEMS FROM A CATASTROPHIC ON OR NEAR PAD FAILURE WITH RELEASE OF RADIOACTIVE MATERIAL

4.4.1.4.2 Chronic Toxicity Effects

A great deal of controversy has surrounded estimates made of the impact of chronic radiation on behavior, somatic (cellular) and reproductive health of exposed plant and animal populations.[4-24] Recent analysis seems to support the contention that exposure to chronic radiation (exceeding 3 mrem/yr for mammals) could cause significant mutagenic effects resulting in increased offspring abnormalities.

Three chronic effects can potentially result within the localized region contaminated from the abnormal event: (1) increases in genetic damage, (2) increases in serious somatic damage, and (3) productivity decreases. Estimates of increases in diseases caused by dominant and x-chromosome-linked recessive mutations would have to be made for a minimum of one generation following the catastrophic event. For example, Tables 4-9 and 4-10 show specific genetic and cytogenetic damage to mammals based on 5 rems per generation.

A major, but not readily quantifiable, effect of chronic irradiation is loss of productivity, loss of survival potential, or increasing susceptibility to disease. This effect can be exhibited in plant, animal, or human populations. A large fraction of disease and productivity levels is genetically related, but the relationships are ill defined and are species specific. To determine the effect of low level chronic irradiation, as in the case of a catastrophic event during nuclear waste disposal, large numbers of generations, their disease incidence, etc., would have to be studied. While little is known of these processes, body burdens of animals and plants in contaminated environs exist and should be correlated with periodic surveys of disease incidence and species productivities.

Under the hypothesis that the cocoon ruptures and no gravitational settling occurs (particle size $<0.6\ \mu$), lung exposures to animals would be expected to produce significant genetic effects within a 100 km distance from the event (12 rems). Synergistic activities among modes of exposure cannot be quantified based on extant data. If larger particles were generated following troposphere explosion, major dose would be experienced at a relatively short distance downwind from the launch pad (0–20 km). The dose resulting would primarily be ingested and via contact with contaminated surfaces. Exposures could cause increases in genetic effects greater to those shown in Tables 4-9 and 4-10. Biotic populations would be severely affected, many eliminated for an unknown period of time following the event. Effects cannot be accurately predicted in this preliminary analysis.

Chronic effects from nuclide contamination are dependent upon the mix of nuclides involved in the hypothetical event. In terrestrial systems, chronic effects from nuclides would be approximately equal for Mixes No. 1 through No. 3. Mixes No. 4 and No. 5 would probably be cycled through these terrestrial ecosystems more rapidly than Mixes No. 1 through No. 3, but the resulting impact cannot, at this writing, be predicted. Chronic effects of Mixes No. 3 through No. 5 are maximum in aquatic systems due to higher mobilities and higher concentrations of nuclides bioaccumulated, e.g., strontium, cesium, and technetium, respectively.

4.4.1.4.3 Bioaccumulation

Bioaccumulation is a process which may concentrate nuclides within organismic components via inhalation, ingestion, or contact. These accumulations could lead to toxic responses in these organisms or, more probably, in top predators of the various food chains impacted. Table 4-11 lists bioaccumulation factors for fish, invertebrates, and plants for primary nuclides of interest. In general, plant bioaccumulation is greater than that of fish or invertebrates. For fish, strontium and cesium, both metabolic mimics of other natural plant

TABLE 4-9. ESTIMATED EFFECTS OF RADIATION FOR SPECIFIC GENETIC DAMAGE ON MAMMALS FROM 5 REM PER GENERATION

	Current Incidence	Number of New Mutants	Effect of 5 rem Per Generation	
			First Generation	Equilibrium
Chromosomal dominant traits	10,000	2000	50-500	250-2500
X-chromosome-linked traits	400	65	0-15	10-100
Recessive traits	1500	?	few	slow increase

Note: The values given are expected numbers per million live births(4-24).

TABLE 4-10. ESTIMATES OF CYTOGENETIC EFFECTS ON MAMMALS FROM 5 REM PER GENERATION

	Current Incidence	Effect of 5 rem Per Generation	
		First Generation	Equilibrium
Congenital Anomalies			
Unbalanced rearrangements	1000	60	75
Aneuploidy	4000	>5	?
Recognized abortions	35000	55	55
Aneuploidy & polyploidy XO	9000	15	15

Note: Values are based on population of 1 million live births. Unbalanced rearrangements are based on male radiation only.(4-24)

nutrients, exhibit the maximum bioaccumulation when compared to the other nuclides. In contrast, both invertebrates and plants accumulate cesium, americium, europium, and samarium, in the range of 1000–5000 pCi/kg. Plants, in addition, accumulate 1000 pCi/kg tin, zirconium, and selenium.[4-25]

Assuming that major bioaccumulation would occur following the scenario which would generate particles large enough to be deposited on soil, vegetation, and water surfaces, chronic exposures could result. Chronic exposure thresholds would be most likely exceeded for long-lived biotic species, such as predatory fish, fowl, and mammals. Effects would be most significant with Mix No. 3, followed by Mix Nos. 2, 1, 4, and 5, respectively.

4.4.1.4.4 Ecosystem Process Disruption

Effects of any toxicant on processes essential to ecosystem function, such as carbon metabolism and nutrient cycling, are only beginning to be understood.[4-26] While initial analysis does not allow time to develop needed data to predict the effects of a catastrophic on or near pad LV failure on ecosystem processes, some discussion is possible. First, effects on ecosystem processes will be a function of the sensitivity to stress and the stability of the targeted ecosystems. Second, effects which might be detected may be due to radiation dosages, heavy element toxicity, or both. Third, effects of the event, regardless of the mechanisms, not only would result in loss of biological productivity, but would increase the probability that the system will totally collapse due to extensive loss of essential elements from soil under the imposed stress.[4-27]

Sensitivity of the ecosystems surrounding the affected area has not been evaluated. The primary terrestrial systems are coastal lowlands adjunct to a shallow ridge inland. Scrub forest might well, as shown in confined laboratory experiments, tolerate significantly more contaminants than other terrestrial systems.[4-27] Wetlands throughout the area receiving heavy fallout deposition (see 4.4.1.2) may be the most sensitive to the contamination due to the fragility of the wetlands energy budget.[4-28] In aquatic systems, dilution of nuclides deposited would make the probability of acute radiation effects slight; chronic effects and bioaccumulation processes would be dominant. Transport from terrestrial systems of mobile nuclides such as technetium would increase aquatic exposure over longer time intervals. The transport of nutrients being depleted from terrestrial systems could temporarily increase aquatic productivity. This increased production could attenuate or amplify nuclide effects on aquatic processes or biota. Final assessment of the catastrophic event would need to address these questions before satisfactory predictions of ecosystem response could be made.

The mix used would significantly affect ecosystem process effects in both aquatic and terrestrial targets. Nuclides with extremely low mobilities would impact terrestrial systems more than aquatic systems due to the accumulation of the nuclides in the biologically active portion of the environmental strata such as soil. Aquatic systems receiving these nuclides would be relatively unexposed to them after initial settling into the sediment layers. Mix No. 3 might cause significant bioaccumulation of tin and selenium in plants but is fairly balanced by lower concentrations of strontium and cesium, metabolic mimics. Mixes No. 1, No. 2, and No. 4 would lead to higher exposure of terrestrial systems to low mobility nuclides, although the specific nuclide loads vary. Mix No. 5 would expose aquatic systems more rapidly than other mixes due to the initial impact of technetium on the systems in addition to high rates of transport from contaminated terrestrial systems. The effects are unknown at the levels of contamination predicted.

TABLE 4-11. BIOACCUMULATION FACTORS FOR FISH, INVERTEBRATES AND PLANTS FOR THE MOST IMPORTANT ELEMENTS IN ANY OF THE FIVE FUEL MIXES

Element	Bioaccumulation Factor (pCi/kg)[a]		
	Fish	Invertebrate	Plant
Curium	25	1000	5000
Strontium	3000	100	500
Plutonium	3.5	100	350
Americium	25	1000	5000
Cesium	2000	100	500
Europium	25	1000	5000
Neptunium	10	400	300
Samarium	25	1000	5000
Technetium	15	5	40
Tin	4	10	1000
Selenium	170	170	1000
Uranium	2	60	0.5
Zirconium	3.3	6.7	1000
Palladium	10	300	200

Source: Reference 4-25.

(a) Maximum radiation dose in 10^{-9} Ci per kg of dry body mass if organisms are exposed continuously and food source is contaminated.

4.4.1.4.5 Differences Caused by Launch Site Location

Instead of the coastal lowland systems impacted by a catastrophic accident at KSC, an island launch site would threaten tropical ecosystems. The intial assessment of site differences allows several points to be made. First, since tropical systems are more sensitive to disruption than temperate systems, island systems would be expected to be more disrupted.[4-29] Since the island site would be expected to be separated from the mainland by at least 160 km (100 mi), continental impact of the event would probably be negligible (depends on meteorologic conditions at the time of the event). Third, recovery of island systems would be much slower than those impacted near KSC due to low recruitment rates of seedstocks and animals from the mainland. Island systems impacted could not have as much risk of exposing large groundwater bodies or regional contamination due to organism mobility as those systems near KSC. Therefore, local effects would be amplified on the islands and regional impacts attenuated.

4.4.1.5 Human Health and Safety

It is the purpose of this section to give an order-of-magnitude analysis concerning the effects upon human health and safety as a result of an on or near pad catastrophic LV failure with the release of radioactive material. The difficulty in accurate assessment of such effects is great since very few real case studies are available for predictive use[4-24].

Human health risks may be considered as acute, chronic, and consumptive. Health risk in this analysis is defined as the risk of exposure to a given level of nuclides by inhalation, ingestion, or contact.

There is much divergence of opinion on the appropriate use of such health effects estimations at low dose levels. The Environmental Protection Agency has released a policy statement from which the following has been extracted[4-30]:

> "It is the present policy of the Environmental Protection Agency to assume a linear, nonthreshold relationship between the magnitude of the radiation dose received at environmental levels of exposure and ill health produced as a means to estimate the potential health impact of actions it takes in developing radiation protection as expressed in criteria, guides, or standards. This policy is adopted in conformity with the generally accepted assumption that there is some potential ill health attributable to any exposure to ionizing radiation and that the magnitude of this potential ill health is directly proportional to the magnitude of the dose received."

The position recently formulated by the NCRP (National Committee on Radiation Protection and Measurements) follows the assumptions of the EPA position and the following information has been extracted[4-31]:

> "The NCRP, after reviewing recent developments relating to radiation standards for the public, particularly in regard to extrapolated estimates of cancer risk at low doses and low dose rates, takes the position that no change is required at this time in the conclusions set out in NCRP Report No. 39 issued in 1971.* The NCRP position is centered on the principle that the 'lowest practicable' radiation level is the fundamental basis for establishing radiation standards and on the assumption that the most important radiation health effects do not have a dose threshold. On this basis, the setting of radiation protection standards requires consideration of compensatory trade-offs between currently assumed hazards and benefits."

*Consistent with standards of the International Atomic Energy Agency (IAEA) which are similar to the basic radiation safety standards of the International Commission on Radiological Protection (ICRP) and the Federal Radiation Council (FRC).

In view of the above, a detailed dose estimate analysis coupled with a safety analysis of the proposed space waste disposal system is required to make an adequate assessment of the potential impact to the human populations in the launch areas.

4.4.1.5.1 Acute Toxicity Effects

Following a catastrophic event, acute toxicity could result within ~100 km downwind of the event. Figure 4-6 shows population distribution for central Florida in relation to the KSC launch site.

The biological effects of ionizing radiation are essentially the same, whether the radioactive material is internal or external to the body provided that the absorbed dose and exposure pathways are similar. In processed nuclear waste the percentage of long half-life alpha emitters is quite high. Thus, when dealing with respirable particles, as assumed here, the potential for inhalation and retention after exposure would be quite high for those exposed. Table 4-12 presents the estimated lung burden, and dose (rems/year) to the lung which could result from this hypothetical event (spring meteorological case—see Section 4.4.1.1) at distances of 20 km and 100 km, respectively, downwind of the event. Approximately 50 rem/year to the lung would be the exposure to someone at 20 km downwind (assuming only one meteorological case); and 12 rem/year would be the exposure to someone at a 100 km downwind distance. Critical organ dose calculations (rems/year) for the same downwind distances are shown in Table 4-13. These data represent partial body irradiation, localized largely with target organs. These doses are much lower than those to the lung.

The doses presented in Table 4-12 are considerably above the standard for unrestricted areas of 0.5 rem/year for whole body, external exposure.[4-23] . Also exceeded is the IAEA recommended maximum exposure to workers in radiation emergencies of 12 rem.[4-32 and 4-33]

The information such as represented in these tables is extremely difficult to interpret, as explained in the BEIR report.[4-24] The values represent internal doses accumulated over a short acute exposure period. Only respiratory pathways were considered, though numerous other environmental pathways will contribute substantially to the chronic exposures, particularly through ingestion of alpha- and soft beta-emitting nuclides. Future studies are expected to include the calculation of acute external whole body exposures.

From Tables 4-14 and 4-15 it appears that acute radiation exposure effects from the hypothesized accident will be only detectable. No radiation exposure deaths beyond the immediate accident site would be expected. Beyond the 20 km distance little clinical evidence of the acute exposure would be present in the population, though blood chemistry changes and some minor symptomology would be anticipated. The acute exposure is not, however, the high risk associated with this accident scenario, but rather the chronic internal exposure to the affected populations.

Impacts of nuclide releases to people in the launch site area would be significant. The Space Shuttle crew would most probably be killed from impact. The accident site, including launch facilities, if involved, would require *deactivation*—an absorbant such as bentonite implaced to minimize nuclide transport through soil and water media—and sealed *permanently*. The limits of the sealants must be determined from radiation surveys of the area since modeling parameters must be verified on site.

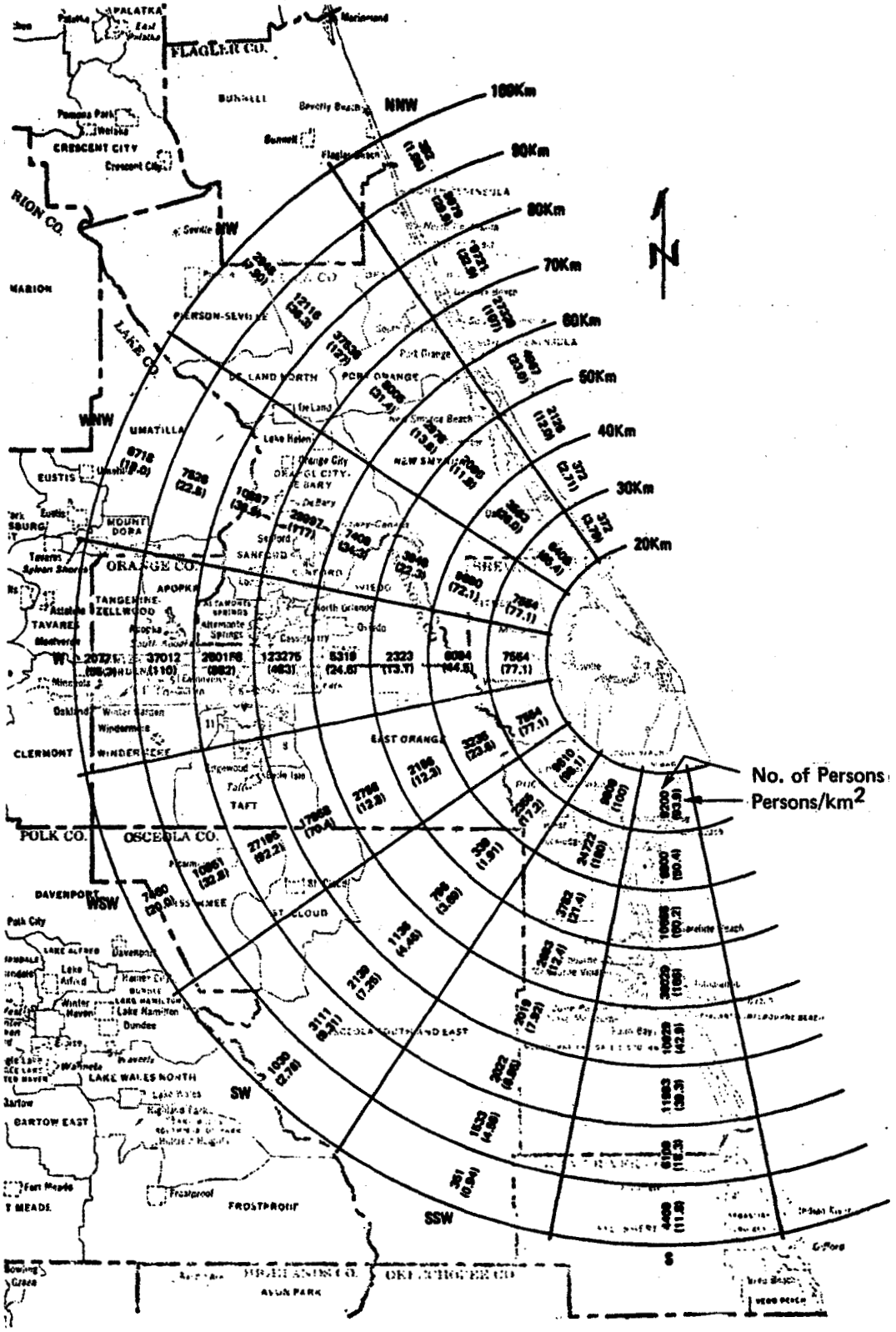


FIGURE 4-6. POPULATION DISTRIBUTION SURROUNDING KSC LAUNCH SITES WHICH COULD BE EXPOSED TO RADIATION FOLLOWING ABNORMAL EVENTS OF SPACE DISPOSAL OPERATIONS.

Source: Reference 4-39.

TABLE 4-12. PREDICTED LUNG BURDENS AND DOSES FOR A WORST-CASE ON PAD CATASTROPHIC LV FAILURE

Nuclide	Effective Energy (Mev)	20 km Downwind		100 km Downwind	
		Lung Burden, μCi	Dose, rems/year	Lung Burden, μCi	Dose, rems/year
Cm 244	60	2.45E-02	2.75E+01	5.24E-03	5.88E+00
Sr 90	1.1	6.80E-01	1.40E+01	1.50E-01	3.08E+00
Pu 238	57	1.16E-03	1.24E+00	2.52E-04	2.68E-01
Am 241	57	1.97E-03	2.10E+00	4.35E-04	4.63E-01
Cs 137	0.41	1.09E-00	8.35E+00	2.45E-01	1.88E+00
Pu 241	0.53	4.15E-03	4.11E-02	9.52E-04	9.43E-03
Am 243	54	2.38E-04	2.40E-01	5.17E-05	5.22E-02
Pu 240	53	6.05E-05	5.99E-02	1.36E-05	1.35E-02
Eu 154	0.86	5.30E-02	8.52E-01	1.15E-02	1.85E-01
Pu 239	53	1.90E-05	1.88E-02	4.22E-06	4.18E-03
Np 237	49	3.74E-06	3.42E-03	8.16E-07	7.47E-04
Cm 245	55	4.49E-06	4.62E-03	1.02E-06	1.05E-03
Sm 151	0.042	1.29E-02	1.01E-02	2.86E-03	2.24E-03
Cm 246	56	8.84E-07	9.25E-04	1.97E-07	2.06E-04
Pu 242	51	8.84E-08	8.43E-05	1.97E-08	2.06E-05
Tc 99	0.094	1.63E-04	2.86E-04	3.60E-05	6.32E-05
Sn 126	0.96	6.26E-06	1.23E-04	1.36E-06	2.44E-05
Se 79	0.094	4.56E-06	8.01E-06	1.02E-06	1.79E-06
U 234	49	4.01E-08	3.67E-06	8.84E-09	8.09E-06
Zr 93	0.020	2.11E-05	7.89E-06	4.69E-06	1.75E-06
U 238	43	1.84E-08	1.48E-05	4.08E-09	3.28E-06
U 236	47	1.56E-09	1.32E-06	3.47E-10	3.05E-07
Pd 107	0.063	1.29E-06	1.52E-06	2.86E-07	3.37E-07
Cs 135	0.066	3.13E-06	3.86E-06	6.80E-07	8.39E-07
U 235	46	8.16E-11	7.01E-08	1.84E-11	1.58E-08
Subtotal			54.4		11.8

Note: Time integrated concentrations obtained from Section 4.4.1.1 for the Spring Meteorological Case (Mix No. 3 assumed).

TABLE 4-13. PREDICTED CRITICAL ORGAN BURDENS AND DOSES FOR A WORST-CASE ON PAD CATASTROPHIC LV FAILURE

Nuclide	Critical Organ	Time-integrated Exposure, $\mu Ci \cdot sec/m^3$	Fraction Reaching Organ	Organ Burden, μCi	Effective Energy, MeV	Organ Mass, gm	Dose, rems/year
			Critical Organs at 20 km Downwind				
Cm 244	Bone	3.6E+02	0.075	1.84E-03	299	7,000	1.40E+00
Sr 90	Bone	1.0E+04	0.12	8.16E-02	5.5	7,000	1.19E+00
Pu 238	Bone	1.7E+01	0.2	2.31E-04	284	7,000	1.75E-01
Am 241	Kidney	2.9E+01	7.5E-03	1.48E-05	57	300	5.82E-02
	Bone	2.9E+01	0.063	1.24E-04	283	7,000	9.38E-01
Cs 137	Total Body	1.6E+04	0.75	8.16E-01	0.59	70,000	1.28E-01
	Liver	1.6E+04	0.05	5.44E-02	0.41	1,700	2.45E-01
	Spleen	1.6E+04	3.8E-03	4.13E-03	0.37	150	1.90E-01
	Muscle	1.6E+04	0.3	3.26E-01	0.59	30,000	1.20E-01
Pu 241	Bone	6.1E+01	0.2	8.30E-04	14	7,000	3.11E-02
Am 243	Bone	3.5E+00	0.063	1.50E-05	272	7,000	1.09E-02
	Kidney	3.5E+00	7.5E-03	1.79E-06	54	300	6.02E-03
Pu 240	Bone	8.9E-01	0.2	1.21E-05	266	7,000	8.57E-03
Eu 154	Kidney	7.8E+02	7.5E-03	3.98E-04	0.76	300	1.88E-02
	Bone	7.8E+02	0.09	4.77E-03	2.7	7,000	3.44E-02
Pu 239	Bone	2.8E-01	0.2	3.81E-06	266	7,000	2.70E-03
			Critical Organs at 100 km Downwind				
Cm 244	Bone	7.7E+01	0.075	3.93E-04	299	7,000	3.13E-01
Sr 90	Bone	2.2E+03	0.12	1.80E-02	5.5	7,000	2.63E-01
Pu 238	Bone	3.7E+00	0.2	5.03E-05	284	7,000	3.81E-02
Am 241	Kidney	6.4E+00	7.5E-03	3.26E-06	57	300	1.15E-02
	Bone	6.4E+00	0.063	2.74E-05	283	7,000	2.06E-02
Cs 137	Total Body	3.6E+03	0.75	1.84E-01	0.59	70,000	2.89E-02
	Liver	3.6E+03	0.05	1.22E-02	0.41	1,700	5.55E-02
	Spleen	3.6E+03	3.8E-03	9.32E-04	0.37	150	4.29E-02
	Muscle	3.6E+03	0.3	7.34E-02	0.59	30,000	2.69E-02
Pu 241	Bone	1.4E+01	0.2	1.90E-04	14	7,000	7.14E-03
Am 243	Bone	7.6E-01	0.063	3.26E-06	272	7,000	2.36E-03
	Kidney	7.6E-01	7.5E-03	3.88E-07	54	300	1.31E-03
Pu 240	Bone	2.0E-01	0.2	2.72E-06	266	7,000	1.93E-03
Eu 154	Kidney	1.7E+02	7.5E-03	8.70E-05	0.76	300	4.12E-03
	Bone	1.7E+02	0.09	1.04E-03	2.7	7,000	7.48E-03
Pu 239	Bone	6.2E-02	0.2	8.43E-07	266	7,000	5.98E-04

Note: Time integrated concentrations obtained from Section 4.4.1.1 for the Spring Meteorological Case (Mix No. 3 assumed).

TABLE 4-14. EFFECTS OF ACUTE IONIZING RADIATION OVER WHOLE BODY--PROBABLE EARLY EFFECTS FROM ACUTE DOSES

0 - 25 rem	No obvious injury
25 - 50 rem	Possible blood changes but no serious injury
50 - 100 rem	Blood-cell changes, some injury, no disability
100 - 200 rem	Injury, possible disability
200 - 400 rem	Injury and disability certain, death possible
400 rem	Fatal to 50%
600 or more rem	Fatal

Source: Reference 4-32.

TABLE 4-15. EFFECTS OF ACUTE IONIZING RADIATION OVER WHOLE BODY--SUMMARY OF CLINICAL EFFECTS

Range	0 to 100 rem Subclinical range	100 to 1000 rem Therapeutic range			Over 1000 rem Lethal range	
		100 to 200 rem	200 to 600 rem	600 to 1000 rem	1000 to 5000 rem	Over 5000 rem
		Clinical surveillance	Therapy effective	Therapy promising	Therapy palliative	
Incidence of vomiting	None	100 rem: 5% 200 rem: 50%	300 rem: 100%	100%	100%	
Delay time	–	3 hours	2 hours	1 hour	30 minutes	
Leading organ	None	Haematopoietic tissue			Gastrointestinal tract	Central nervous system
Characteristic signs	None	Moderate leukopaenia	Severe leukopaenia; purpura; haemorrhage; infection. Epilation above 300 rem		Diarrhoea; fever; disturbance of electrolyte balance	Convulsions; tremor; ataxia; lethargy
Critical period post-exposure	–	–	4 to 6 weeks		5 to 14 days	1 to 48 hours
Therapy	Reassurance	Reassurance; haematologic surveillance	Blood transfusion; antibiotics	Consider bone marrow transplantation	Maintenance of electrolyte balance	Sedatives
Prognosis	Excellent	Excellent	Good	Guarded	Hopeless	
Convalescent period Incidence of death	None None	Several weeks None	1 to 12 months 0 to 80% (variable)	Long 80 to 100% (variable)	– 90 to 100%	
Death occurs within	–	–	2 months		2 weeks	2 days
Cause of death	–	–	Haemorrhage; infection		Circulatory collapse	Respiratory failure; brain edema

Source: Reference 4-32.

Waste mix involved in a catastrophic event would affect acute exposure risks (see Table 4-16). Since technetium (Mix No. 5) is the most mobile mix, it would present the least threat to humans directly and increase the threat from chronic exposure by its presence in water supplies and availability in food chains. Mixes No. 2 and No. 3 are considered risky due to high concentrations of strontium and cesium which are metabolically active. Mixes No. 1, No. 2, and No. 3 provide short-term exposure to highly toxic alpha emitters such as Pu. Mix No. 4 is primarily less toxic except for cesium and americium which are bioconcentrated.

4.4.1.5.2 Chronic Toxicity Effects

A catastrophic event, such as that defined above, could significantly affect human health within the population wheel (see Figure 4-6). Doses resulting from inhalation pathways (rems/year) for the accident scenario are presented in Tables 4-12, 4-13, and 4-16. Particle size distribution would determine whether the major mode of exposure were inhalation or assimilation. At increasing distance from release point, danger from heavier particles will decrease.

Calculations for low dose responses are difficult.[4-24] However, final assessment should be made using calculations for low dosages made by assuming that the relationship between the lowest accurate measurements and zero-induced effect is linear. This assumption is plausible for mutations and chromosomal breaks and is conservative for other effects such as disjunction. Chronic effects should be predicted from chronic or fractionated doses on experimental animals rather than large acute doses. Four effects can be determined as chronic toxicity.

First, natural background radiation (~0.1 rems/year) would significantly increase in the area. It would seem from this initial analysis that radiation levels would be increased measurably over the area of the population wheel (see Figure 4-6) for many generations, dependent upon the half-life of the nuclides released. The effect would be inversely related to half-life of the nuclides.

Second, risk for specific genetic damage as a result of a catastrophic event would increase within the area. First generation damage could approximate a 5 to 50 percent increase in chromosomal dominant trait abnormalities and 25 to 250 percent increase at equilibrium per 5 rem/generation dosage. Damage to x-chromosome-linked traits and recessive traits would be much less.[4-24] Cytological genetic effects would increase within the affected area. Congenital anomalies would be expected to increase 12 percent for the first generation and 15 percent at equilibrium per 5 rems/generation dosages. Recognized abortions would be expected to increase 2 percent for 5 rems/generation increase.[4-24]

Third, serious disabilities would potentially be increased within the area if continuous exposure over 30 years were 5 rems. The risk would approximate an increase of 5 to 50 percent in mutation-caused disease. These effects are difficult to predict since the genetic relationship to disease susceptibility is still not well understood in human or other mammal populations.[4-24]

Finally, significant increases in ill health, including incidence of tumors and other carcinogenic responses, can be expected. This effect is the least understood of all nuclide responses in human populations. The effect of waste mix cannot be determined at this level of investigation, even though doses to body organs would vary with mix (Table 4-16).

TABLE 4-16. PREDICTED ORGAN BURDENS AND DOSES FOR A WORST-CASE CATASTROPHIC LV FAILURE FOR VARIOUS NUCLIDES IN DIFFERENT MIX OPTIONS

Nuclide	Mix	Organ[(a)]	Distance, km	Time-integrated Exposure, $\mu Ci \cdot sec/m^3$	Fraction Reaching Organ	Organ Burden, μCi	Effective Energy, MeV	Organ Mass, g	Dose, rems/year
Pu 238	2	Lung	20	2400	6.8E-05	1.63E-01	57	1000	1.74E+02
Pu 238	2	Lung	100	530	6.8E-05	3.60E-02	57	1000	3.83E+01
Pu 238	2	Bone	20	2400	0.2	3.26E-02	284	7000	2.47E+01
Pu 238	2	Bone	100	530	0.2	7.21E-03	284	7000	5.46E+00
Pu 240	2	Lung	20	115	6.8E-05	7.82E-03	53	1000	5.75E+00
Pu 240	2	Lung	100	25	6.8E-05	1.70E-03	53	1000	1.68E+00
Pu 240	2	Bone	20	115	0.2	1.56E-03	266	7000	1.11E+00
Pu 240	2	Bone	100	25	0.2	3.40E-04	266	7000	2.40E-01
Cm 244	4	Lung	20	838	6.8E-05	5.70E-02	60	1000	6.39E+01
Cm 244	4	Lung	100	185	6.8E-05	1.26E-02	60	1000	1.41E+01
Cm 244	4	Bone	20	838	0.075	4.27E-03	299	7000	3.41E+00
Cm 244	4	Bone	100	185	0.075	9.44E-04	299	7000	7.50E-01

(a) In all cases the bone is the critical organ.

4.4.1.5.3 Consumptive Effects

The intake of water, plant and animal tissue which contains nuclides released from the catastrophic event represents an indirect exposure pathway which may intensify health effects from the event. The ecosystems surrounding KSC are water-rich and shallow aquifers are used for irrigation and domestic consumption (see Table 4-17). Table 4-18 shows land use and irrigated land use of the area 50 km surrounding KSC. Following such an accident, nuclide concentrations would have to be monitored routinely to determine plant and animal body burdens prior to human consumption.

Dose to man through consumption will primarily be the metabolically active nuclides (strontium and cesium) through bioaccumulation pathways into fish. Pathways through terrestrial plants and domestic animals are less important in terms of total bioaccumulated nuclide burden. However, the diet of U.S. citizens highly favors terrestrial to aquatic protein sources. Consequently, total exposure might be dominated by the terrestrial domestic animal food chain. Table 4-19 shows landings of commercial seafood in the area surrounding KSC. The proportion of the harvest consumed by residents within the affected area and the actual body burdens of seafood would have to be determined before an accurate assessment could be made.

Highly mobile nuclides, such as technetium, could significantly be transported to man by consumption processes. Desert food chain studies, models of nuclide movement through desert ecosystems, and use of chemical characteristics have led to predictions of bioaccumulation less than have been measured in the eastern U.S. ecosystems.[4-34] Each of the five mixes would behave differently and the potential for consumptive movement to man would have to be individually examined.

4.4.1.5.4 Differences Caused by Launch Site Location

If launch were from an island in the Atlantic near the tropical zone of South America, the effects to human populations would be greatly reduced. No acute effects would be expected to workers, if adequate safety measure had been taken. Chronic effects could be expected only if worker populations were resident over long periods of time.

Consumptive effects should be the only significant risks posed using the island launch sites. Primary problems would be strontium and cesium accumulation into fish tissue and human assimilation. Acquisition of freshwater on the island may have to be limited to deep aquifers, depending on water and sediment nuclide concentrations.

4.4.2 Launch Vehicle Explosion and Fire at High Altitude or Reentry and Burnup of the Nuclear Waste Payload from Orbit

As discussed in Section 4.4, the abnormal event considered in this section is a launch vehicle explosion and fire at high altitude or reentry and burnup of the nuclear waste payload from orbit with a major impact to the upper atmosphere, followed by chronic impact to the lower atmosphere.

TABLE 4-17. PUBLIC WATER AQUISITION IN THE FIVE-COUNTY AREAS SURROUNDING KSC

County	Well Depth(m)	Shallow Water Table Pleistocene	Floridan Aquifer Formations	
			Ocala	Avon Park
Brevard	12-24	X		
Indian River	37	X		
Orange	43-128		X	
Seminole	61-121		X	
Volusia	47-105			X

Source: Reference 4-39.

TABLE 4-18. LAND USE AND IRRIGATION IN THE 50 KM RADIUS OF KSC

Year of Basis	Total Area	Hectares (%)						
		Citrus	Other Crops	Improved Pasture	Unimproved Pasture	Forestland	Misc. Agricultural	Non-Agricultural
1965	378	7.4[a] (1.9)	--	25.5[c] (6.4)	65.8 (16.5)	95.3 (23.9)	64.8 (16.3)	46.7 (11.7)
2020[e]	398	22.6[b] (5.7)	2.0 (0.5)	38.5[d] (9.7)	5.2 (1.3)	92.1 (23.2)	29.3 (7.4)	97.9 (24.6)

(a) 1.0 hectares irrigated.
(b) 9.0 hectares irrigated.
(c) 5.5 hectares irrigated.
(d) 8.3 hectares irrigated.
(e) 1.9 hectares irrigated other crops. Irrigated areas exceed total in some units due to double cropping.

Source: Reference (4-39).

TABLE 4-19. LANDINGS OF COMMERCIALLY IMPORTANT SEA LIFE IN THE FOUR COUNTIES AROUND KSC AND ON THE FLORIDA ATLANTIC COAST

Region	Category (kilograms)			
	Total Fish	Total Shellfish	Total Shrimp	Total Other
East Coast of Fla.	17,546,880	4,181,587	2,350,213	11,533
Brevard	1,135,288	1,047,570	292,473	—
Indian River	687,778	328,304	—	65
St. Lucie	1,191,302	74,203	728	—
Volusia	567,100	65,902	109,592	1,906

Source: Reference 4-39.

Several accidents have been postulated which could lead to significant release of waste material at high altitudes. Most of these situations would involve a failure of the launch vehicle (e.g. guidance system failure, SRM case failure, intrusive act, etc.) with insertion into a relatively short-lived orbit and subsequent orbital decay and reentry. Under severe conditions (explosion, tumbling, structural failure, etc.) the cocoon and container holding the nuclear waste could rupture and disperse radioactive waste to the upper atmosphere. Without a detailed safety analysis it would be difficult to make any meaningful projections about the survivability of the protective cocoon. For the purposes of this preliminary analysis we assume the worst case and project that all of the waste material is released and is in the respirable (<4 micron) particle size range.

There also exists the possibility of accidents resulting from maneuvers with the Orbit Transfer Vehicle (OTV). Accidental reentry could result from a misoriented burn during one of the orbital maneuvers or an explosion of a fully fueled OTV. In this case, there would be no protective cocoon for the waste material and if reentry were to occur it is virtually certain that complete burnup in the upper atmosphere would cause worldwide dispersion of the waste material.

The United States has launched 20 payloads incorporating plutonium-238 fueled RTG systems. Five of these were Apollo Lunar Missions which left their RTGs (SNAP-27s) on the surface of the Moon to power various experiments. Two others were NASA's Pioneer 10 and 11 missions to explore Jupiter and Saturn; their SNAP-19 RTGs will eventually leave the solar system. The two most recent launches were those of NASA's Viking spacecraft, now on their way to explore Mars.

Three launches aborted at various times, resulting in their payloads' RTGs returning to Earth. The first was the 1964 incident involving a SNAP-9A powered navigational satellite. The second involved a NASA meteorological satellite in 1968. This mission's launch vehicle went off course shortly after launch and was destructed; the satellite's SNAP-19 RTGs were recovered from the ocean intact. The third involved the 1970 Apollo 13 mission, which had to be curtailed when an explosion damaged the spacecraft. In conjunction with the safe recovery of the three astronauts, the SNAP-27 was successfully targeted to deposit intact in the Tonga Trench in the South Pacific, where it is effectively isolated from man's environment.

The remaining eight launches all involved satellites which are currently in orbit around the Earth. Characteristics of these satellites, their RTG systems, and their orbits are summarized in Table 4-20. The "Disposal Mode" column indicates the manner in which each RTG was designed to respond to atmospheric reentry. Before 1967, RTGs were designed to burn up at high altitude to enhance the dispersal of their plutonium, as the SNAP-9A abortively launched in 1964 did. Since then, RTG systems (including the LES-MHW-RTG) have been designed to survive such reentry intact to allow their recovery on Earth and the return of their plutonium inventories to positive control.

4.4.2.1 Air Quality

The region of release considered in this section is about 10 to 100 kilometers above the surface of the Earth. The objective of this section is to provide a preliminary approach to assessing the environmental impacts of fallout and dispersion of radioactive waste material, assuming that the waste material is subjected to a series of events leading to reentry and total burnup. The case where the waste material survives reentry intact is covered in Sections 4.4.3 (ocean impact) and 4.4.4 (land impact).

TABLE 4-20. CHARACTERISTICS OF SATELLITES CONTAINING RTG's

S/C	Launch Date	Period, min	Inc., deg	Apogee km	Perigee km	Power Source	Inventory of Pu-238 at Launch (curies)	Expected Orbital Lifetime, years	Disposal Mode
Transit 4A	6/29/61	103.7	66.8	993	881	SNAP-3	1,800	570	Burnup
Transit 4B	11/15/61	105.7	32.4	1103	953	SNAP-3	1,800	1200	Burnup
Transit 5BN1	9/28/63	107.3	89.8	1135	1072	SNAP-9A	17,000	1900	Burnup
Transit 5BN2	12/5/63	107.0	89.9	1119	1067	SNAP-9A	17,000	1800	Burnup
Nimbus III	4/14/69	107.3	99.7	1135	1074	SNAP-19	37,000	3600	Intact Reentry
"Transit" (TRIAD 01-0X)	9/2/72	100.6	90.1	838	742	RTG	24,000	150	Intact Reentry
LES-8	3/14/76	1440	25.0	35,900	35,900	MHW-RTG	149,600	$>10^6$	Intact Reentry
LES-9	3/14/76	1440	25.0	35,900	35,900	MHW-RTG	149,600	$>10^6$	Intact Reentry

Note: A 5500 kg nuclear waste payload (Mix #3) would contain $\sim 10^4$ curies of Pu^{238} and a total of $\sim 10^7$ curies when all nuclides are included.

The eventual inhalation of small particles of high level waste released as a result of destructive reentry of the waste and its container is probably the most obvious route of exposure to man and animals. Eventual deposition on the land, resuspension, ingestion, and other routes are of less immediate concern and would provide a lesser impact.

The particles of interest will be those with diameters of less than approximately 4 microns and it will be assumed that all of the waste material is vaporized into particles of this size or smaller. Eventually this material will reach the lower regions of the Earth's atmosphere and the particles will be inhaled and retained in the lung as predicted by the ICRP lung model.[4-35] Figure 4-7, radionuclide concentration in surface air at Richland, Washington, gives indication of how high altitude releases (weapons tests) can result in changes in ground level concentration of radionuclides. For a comparison, the total amount of ^{90}Sr released to the upper atmosphere as a result of all atomic explosions through 1962 (signing of the Nuclear Test-Ban Treaty) was 19.3 megacuries. Thus, the amount of ^{90}Sr which potentially could be released from one accident involving Mix No. 3 amounts to about 40% of that released from all nuclear devices through 1962.

Rather extensive and comprehensive computer models have been generated and are available for detailed analysis of atmospheric circulation and transport of small particles released at high altitudes.[4-36,4-37,4-38] Application of these models requires extensive input description and significant computer time and would be inappropriate for a preliminary analysis of potential environmental problems. A simplified analysis used by the AEC (now ERDA) Space Nuclear Systems Division based on empirical observations of the downward transport of the SNAP-9A debris is used here, and is outlined in detail in Reference 4-39.

The downward transport of fine particle debris from the SNAP-9A has been reported by Krey.[4-40] Up to two years may be required for this type of material to descend to levels of significance in the troposphere. A half-life removal-time of eight months has been assumed for removal from the lower stratosphere of the vaporized waste material for purposes of estimating time dependent exposure[4-39].

In assessing the possible latitudinal distribution of exposure it has been assumed that the released particles will be preferentially deposited in the mid-latitudes and that the ground deposition pattern will be similar to that observed for strontium-90 and plutonium-238. A Gaussian curve has been fitted to the empirical data for the latitudinal distribution of strontium-90 (cumulative deposition mCi/km^2) as of the end of 1965 for both hemispheres (Figure 4-8)[4-39]. The distribution of waste material over the Earth's surface would be generally a function of the latitude where the material enters the atmosphere (injection latitude). The distribution of the strontium-90 data skews toward the mid-latitudes of the northern hemisphere in Figure 4-8 because past weapons tests were generally conducted at these locations.

To assess the distribution of fuel released from a variety of injection latitudes, a generalization was made from the strontium-90 data. Assumptions are that the distribution will be generally Gaussian in each hemisphere with a null point at the Equator and maximums occuring at mid-latitudes. A plot of the distribution of a unit source as a function of injection latitude is shown in Figure 4-9. From curves such as these, the fraction of source term falling into equal area latitude bands can be determined. Using these curves and the source term of

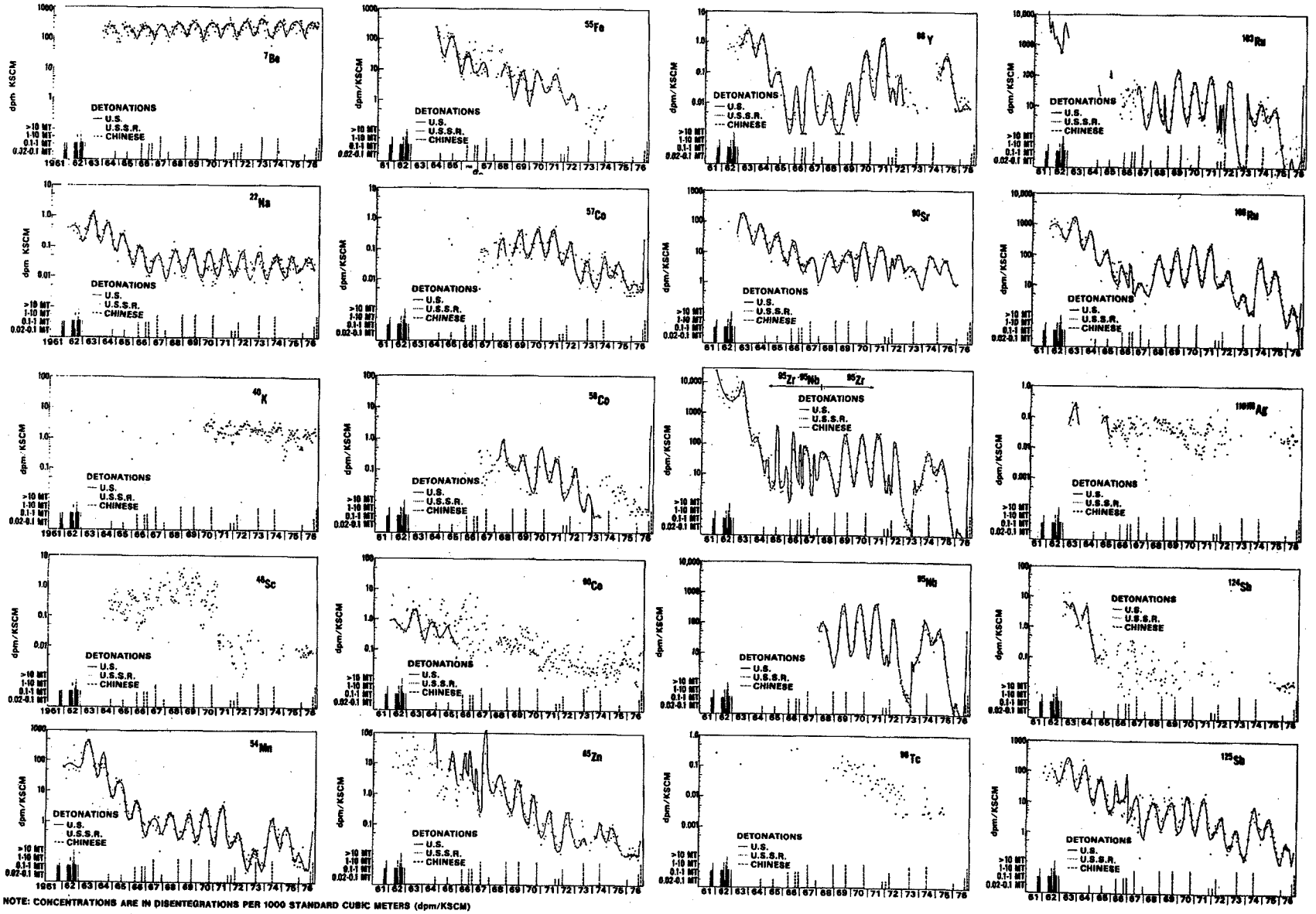


FIGURE 4-7. RADIONUCLIDE CONCENTRATION IN SURFACE AIR AT RICHLAND, WASHINGTON

Source: Reference 4-46.

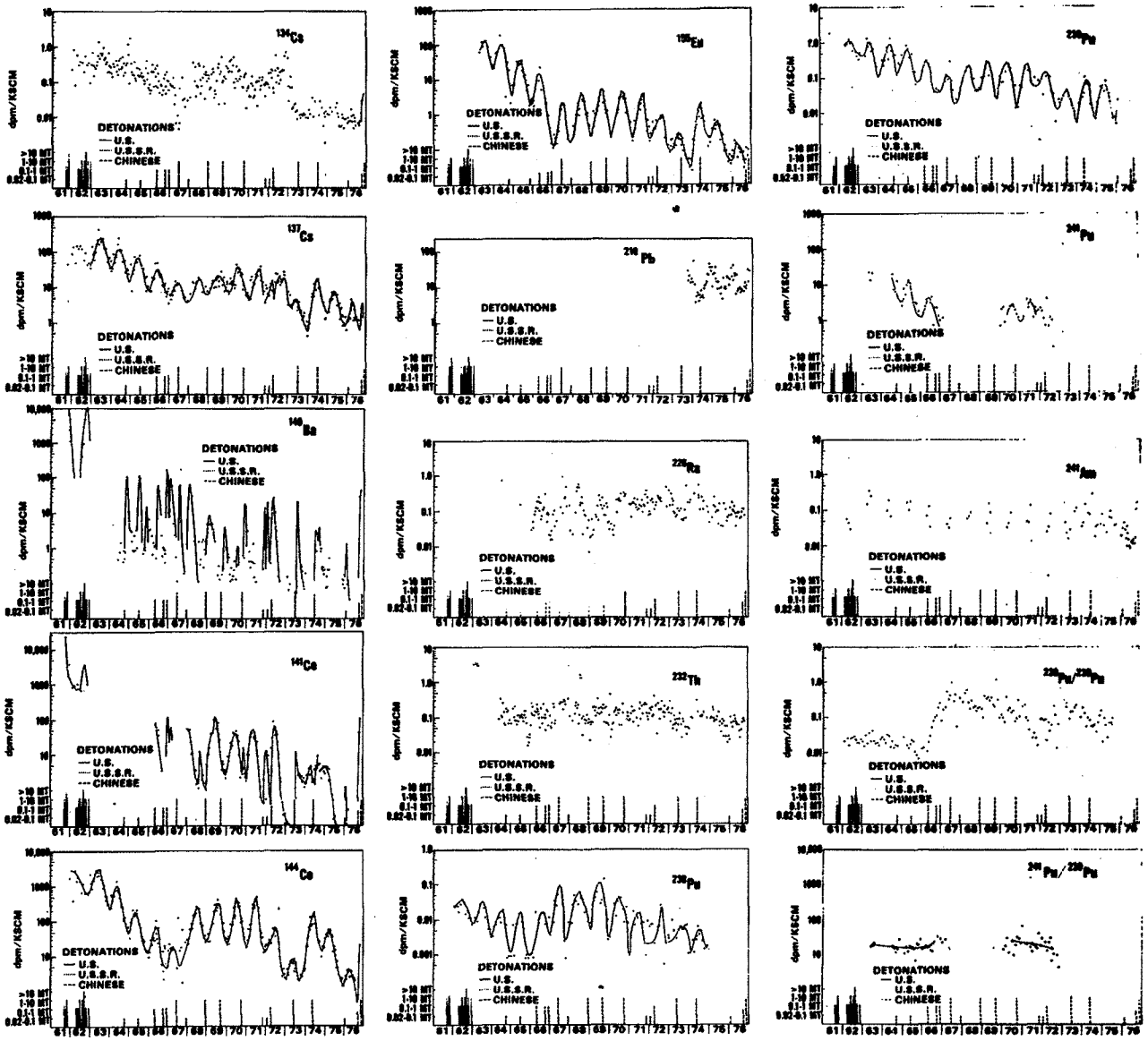


FIGURE 4-7. (CONTINUED)

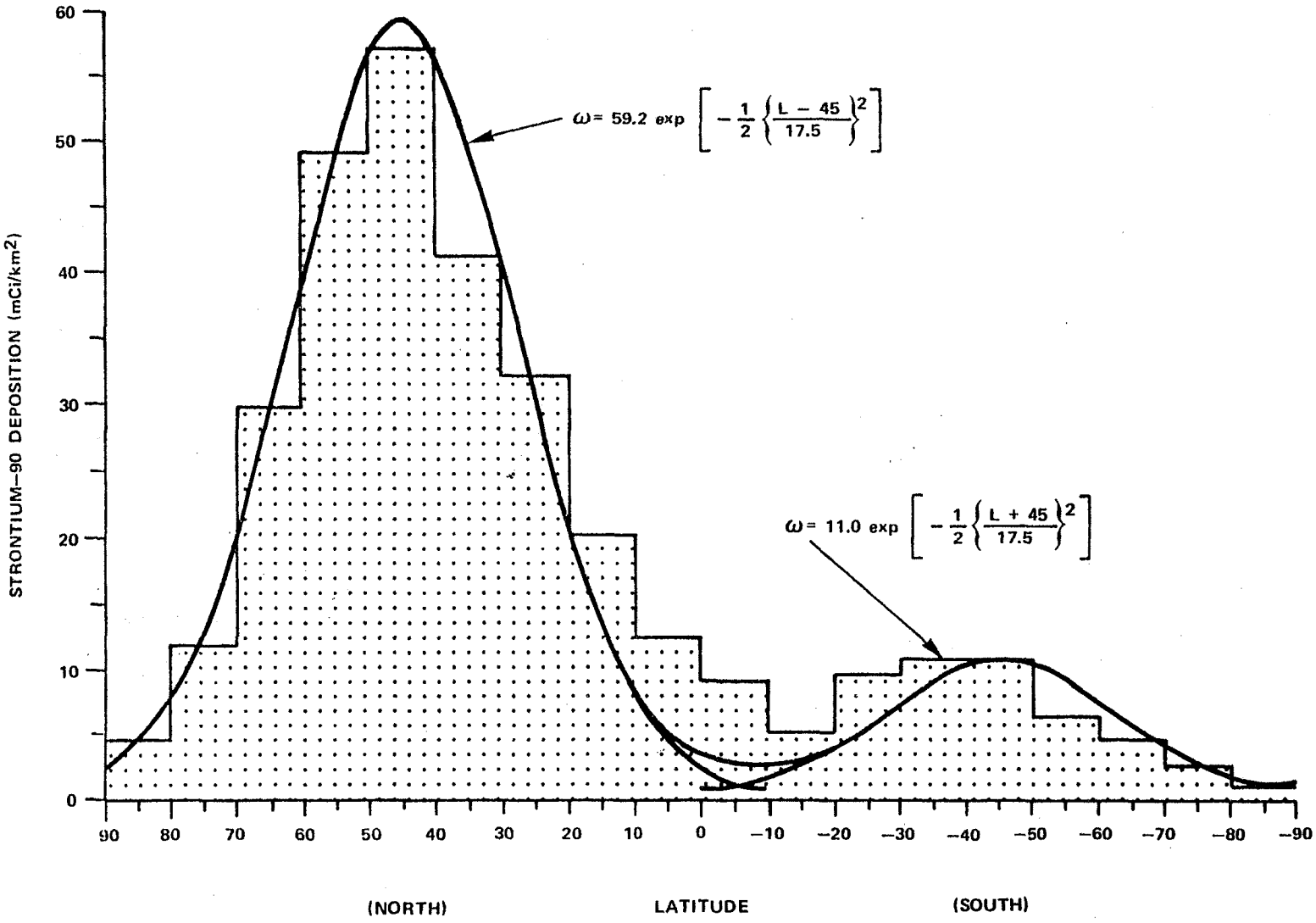


FIGURE 4-8. STRONTIUM-90 DEPOSITION AS A FUNCTION OF LATITUDE

Source: Reference 4-39.

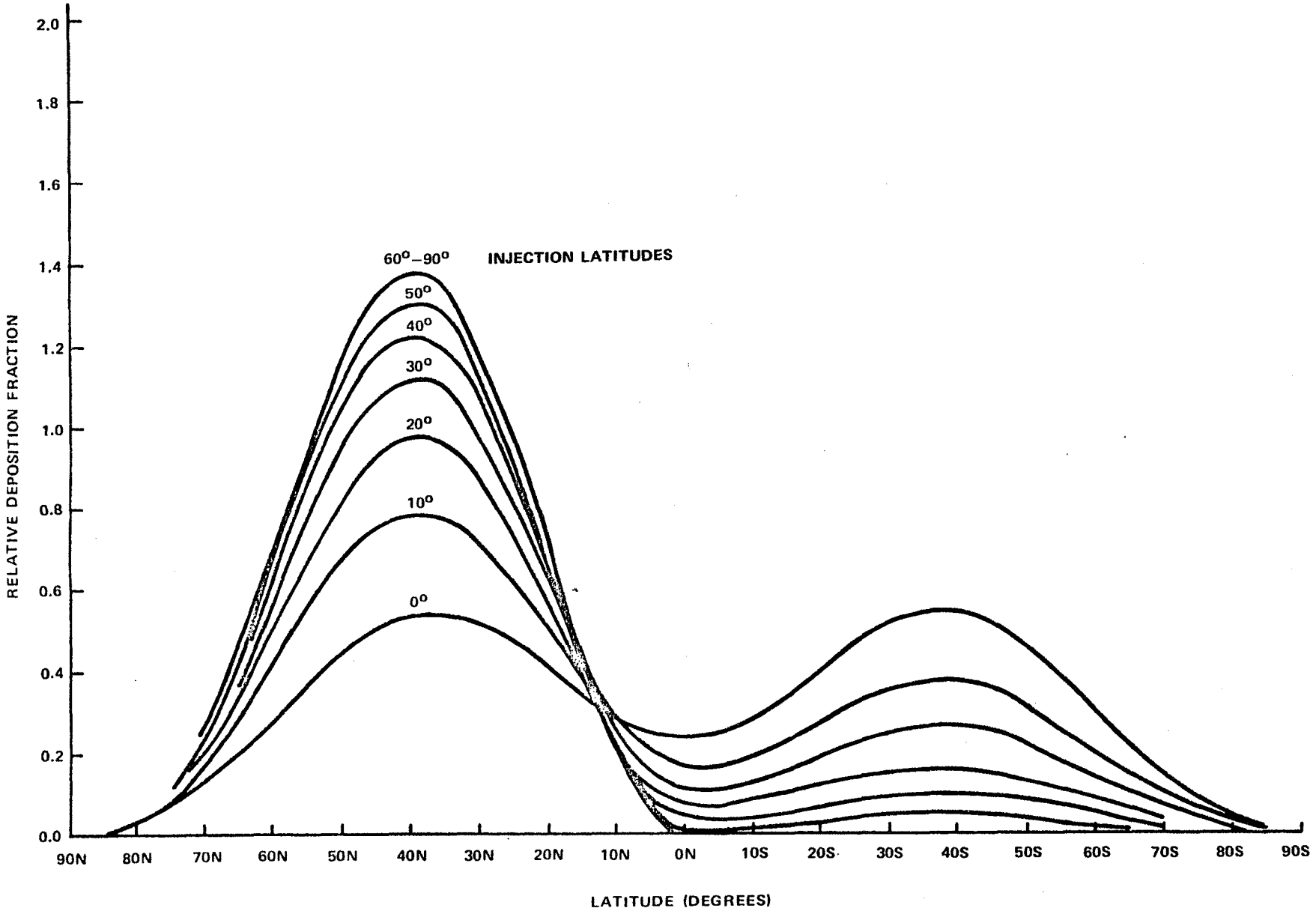


FIGURE 4-9. DEPOSITION OF SMALL PARTICLES ($\leq 4\mu$) RELEASED AT HIGH ALTITUDE AS A FUNCTION OF INJECTION LATITUDE

Source: Reference 4-39.

waste material injected into the atmosphere, the integrated airborne concentration in a given equal area latitude band from a release in an injection latitude band is given by:[4-39]

$$\psi_{ik} = \frac{Q\, f_{ik}}{A\, V_o}$$

where

ψ_{ik} = Integrated airborne concentration in equal area latitude band k from a release in injection latitude band i, C_i-sec/m^3

Q = Quantity of released waste material, μC_i

f_{ik} = Fraction of waste material released in injection latitude band i falling into equal area latitude band k

A = Area of each equal area latitude band, m^2 (2.55×10^{13} m^2)

V_o = Deposition velocity, m/sec (2.0×10^{-2} m/sec).

For the purposes of this study, two injection latitude bands were picked. The first is for an injection latitude of 0° which corresponds to an ultimate failure at the Equator. The second is for an injection latitude of 40° N which leads to the maximum integrated airborne concentration in the latitudes of greatest potential population exposure.

Table 4-21 gives the maximum integrated airborne concentrations for 25 of the more hazardous nuclides (see Section 4.4.1.1) for the injection latitudes of 0° and 40° N. Quantities of waste material for each of the mixes were those indicated in Table 4-6 (Section 4.4.1.1). For each of these cases the maximum integrated airborne concentration occurs in the equal area latitude band bounded by 53° 07′ N by 44° 27′ N (in the case of the 0° injection latitude another equal maximum occurs in the southern hemisphere at the same latitude band).

4.4.2.2 Water and Land Quality

There are several impacts on water and land quality which could result from the high altitude release of radioactive material. In the section on air quality, it was assumed that the material was all vaporized into particles less than 4 microns in diameter. This material will eventually be deposited over the water and on the land rather uniformly throughout areas determined by where the material was injected. If, on the other hand, the material is not vaporized but assumes some particle size distribution with an appreciable fall velocity, then perhaps only a small area of the Earth will be affected. The problem then will be a large quantity of radioactive material distributed over a small area with resultant high dose levels.

In an elevated release, the larger and heavier particulate material differs in behavior from the fine or vapor type material, in that, the larger particles reach the ground as a result of gravitational settling. This is a complex problem and only a general approach can be attempted here.

Using the information available for the particle size distribution considered characteristic of fractured plutonium dioxide fuel[4-39] (see Figure 4-10) some preliminary calculations can be made using only the particle size distribution below 2000 microns. Particles greater than 2000

TABLE 4-21. MAXIMUM INTEGRATED AIRBORNE CONCENTRATIONS AT 0° AND 40°N LATITUDE INJECTIONS FOR VARIOUS NUCLEAR MIX OPTIONS RESULTING FROM AN UPPER ATMOSPHERE BURNUP OF A 5500 KG WASTE PACKAGE(a)

	Mix No. 1				Mix No. 2				Mix No. 3				Mix No. 4			
			Ψ_{max} μCi·sec/m^3	Ψ_{max}			Ψ_{max} μCi·sec/m^3	Ψ_{max}			Ψ_{max} μCi·sec/m^3	Ψ_{max}			Ψ_{max} μCi·sec/m^3	Ψ_{max}
Nuclide	Mass, kg	Activity, μCi	0°	40°N	Mass, kg	Activity, μCi	0°	40°N	Mass, kg	Activity, μCi	0°	40°N	Mass, kg	Activity, μCi	0°	40°N
Curium 244	0.117	9.7x10+09	1.3x10-03	3.3x10-03	2.33	1.9x10+11	2.6x10-02	6.5x10-02	3.02	2.5x10+11	3.5x10-02	8.6x10-02	8.86	7.4x10-11	1.0x10-01	2.5x10-01
Strontium 90	1.93	2.8x10+11	3.9x10-02	9.6x10-02	38.3	5.5x10+12	7.6x10-01	1.9x10+00	49.7	7.2x10+12	9.9x10-01	2.5x10+00	0	0	0	0
Plutonium 238	5.34	9.3x10+10	1.3x10-02	3.2x10-02	106	1.8x10+12	2.5x10-01	6.2x10-01	0.687	1.2x10+10	1.7x10-03	4.1x10-03	0.402	7.0x10+09	9.6x10-04	2.4x10-03
Americium 241	0.250	8.1x10+08	1.1x10-04	2.8x10-04	4.97	1.6x10+10	2.2x10-03	5.5x10-03	6.44	2.1x10+10	2.9x10-03	7.2x10-03	18.9	6.1x10+10	8.4x10-03	2.1x10-02
Cesium 137	4.55	4.5x10+11	6.2x10-02	1.5x10-01	90.2	8.9x10+12	1.2x10+00	3.1x10+00	117	1.2x10+13	1.8x10+00	4.1x10+00	343	3.4x10+13	4.7x10+00	11.6x10+00
Plutonium 241	3.06	3.5x10+11	4.8x10-02	1.2x10-01	61.1	6.9x10+12	9.5x10-01	2.4x10+00	0.395	4.5x10+10	6.2x10-03	1.5x10-02	0.233	2.6x10+10	3.6x10-03	8.9x10-03
Americium 243	0.518	9.6x10+07	1.3x10-05	3.3x10-05	10.3	1.9x10+09	2.6x10-04	6.5x10-04	13.4	2.5x10+09	3.4x10-04	8.6x10-04	39.1	7.2x10+09	9.9x10-04	2.5x10-03
Plutonium 240	21.1	4.8x10+09	6.6x10-04	1.6x10-03	420	9.5x10+10	1.3x10-02	3.3x10-02	2.72	6.2x10+08	8.5x10-05	2.1x10-04	1.6	3.6x10+08	5.0x10-05	1.2x10-04
Europium 154	0.150	2.2x10+10	3.0x10-03	7.6x10-03	2.97	4.3x10+11	5.9x10-02	1.5x10-01	3.85	5.6x10+11	7.7x10-02	1.9x10-01	11.3	1.6x10+12	2.2x10-01	5.5x10-01
Plutonium 239	24.6	1.5x10+09	2.1x10-04	5.2x10-04	490	3.0x10+10	4.1x10-03	1.0x10-02	3.18	2.0x10+08	2.8x10-05	6.9x10-05	1.86	1.1x10+08	1.5x10-05	3.8x10-05
Neptunium 237	2.22	1.5x10+06	2.1x10-07	5.2x10-07	44.2	3.0x10+07	4.1x10-06	1.0x10-05	57.2	3.9x10+07	5.4x10-06	1.3x10-05	168	1.2x10+08	1.7x10-05	4.1x10-05
Curium 245	0.012	1.9x10+06	2.6x10-07	6.5x10-07	0.229	3.7x10+07	5.1x10-06	1.3x10-05	0.297	4.8x10+07	6.6x10-06	1.6x10-05	0.869	1.4x10+08	1.9x10-05	4.8x10-05
Samarium 151	0.196	5.3x10+09	7.3x10-04	1.8x10-03	3.91	1.1x10+11	1.5x10-02	3.8x10-02	5.07	1.4x10+11	1.9x10-02	4.8x10-02	14.8	4.0x10+11	5.5x10-02	1.4x10-01
Curium 246	0.0014	3.7x10+05	5.1x10-08	1.3x10-07	0.028	7.4x10+06	1.0x10-06	2.5x10-06	0.037	9.8x10+06	1.4x10-06	3.4x10-06	0.107	2.8x10-07	3.9x10-06	9.6x10-06
Plutonium 242	1.85	7.2x10+06	9.9x10-07	2.5x10-06	36.8	1.4x10+08	1.9x10-05	4.8x10-05	0.238	9.3x10+05	1.3x10-07	3.2x10-07	0.140	5.5x10+05	7.6x10-08	1.9x10-07
Technetium 99	3.93	6.7x10+07	9.2x10-06	2.3x10-05	78.1	1.3x10+09	1.8x10-04	4.5x10-04	101	1.7x10+09	2.3x10-04	5.8x10-04	0	0	0	0
Tin 126	0.094	2.6x10+06	3.6x10-07	8.9x10-07	1.86	5.2x10+07	7.2x10-06	1.8x10-05	2.42	6.8x10+07	9.4x10-06	2.3x10-05	0	0	0	0
Selenium 79	0.026	1.8x10+06	2.5x10-07	6.2x10-07	0.526	3.6x10-07	5.0x10-06	1.2x10-05	0.682	4.8x10+07	6.6x10-06	1.6x10-05	0	0	0	0
Uranium 234	0.524	3.2x10+06	4.4x10-07	1.1x10-06	0.052	3.2x10+05	4.4x10-08	1.1x10-07	0.068	4.2x10+05	5.8x10-08	1.4x10-07	0.039	2.4x10+05	3.3x10-08	8.2x10-08
Zirconium 93	3.39	8.8x10+06	1.2x10-06	3.0x10-06	67.7	1.8x10+08	2.5x10-05	6.2x10-05	87.5	2.3x10+08	3.2x10-05	7.9x10-05	0	0	0	0
Uranium 238	4405	1.5x10+06	2.1x10-07	5.2x10-07	438	1.5x10+05	2.1x10-08	5.2x10-08	566	1.9x10+05	2.6x10-08	6.5x10-08	333	1.1x10+05	1.5x10-08	3.8x10-08
Uranium 236	2.00	1.3x10+05	1.8x10-08	4.5x10-08	0.199	1.3x10+04	1.8x10-09	4.5x10-09	0.257	1.6x10+04	2.2x10-09	5.5x10-09	0.151	9.5x10+03	1.3x10-09	3.3x10-09
Palladium 107	1.15	5.5x10+05	7.6x10-08	1.9x10-07	22.8	1.1x10+07	1.5x10-06	3.8x10-06	29.6	1.4x10+07	1.9x10-06	4.8x10-06	0	0	0	0
Cesium 135	1.46	1.3x10+06	1.8x10-07	4.5x10-07	29.0	2.6x10+07	3.6x10-06	8.9x10-06	37.6	3.3x10+07	4.5x10-06	1.1x10-05	110	9.7x10+07	1.3x10-05	3.3x10-05
Uranium 235	3.16	6.8x10+03	9.4x10-10	2.3x10-09	0.314	6.8x10+02	9.4x10-11	2.3x10-10	0.407	8.8x10+02	1.2x10-10	3.0x10-10	0.238	5.1x10+02	7.0x10-11	1.8x10-10

(a) For Mix No. 5 - Mass = 2547 kg (T_c-99)
Activity = 4.4x10+10 μCi
Ψ_{max}, 0° = 6.1x10-03 μCi·sec/m^3
Ψ_{max}, 40°N = 1.5x10-02 μCi·sec/m^3.

micron diameter would be only somewhat affected by the winds and therefore would be expected to impact in a relatively small area below the release site. Since it is not known quantitatively the distribution of waste material which would be greater than 2000 microns in diameter, it will be assumed that all of the waste material has the particle size distribution shown in Figure 4-10. It is also assumed that the horizontal particle velocity is equal at all times to the corresponding horizontal air velocity and that the particle vertical velocity is equal to the sum of the particle fall velocity and the local vertical air velocity.

The path of a particle through the atmosphere depends not only on the particle's characteristics and the wind patterns, but also on the dynamic properties of the atmosphere. These properties (density, speed of sound, viscosity, and the mean free path of the air molecules) depend on temperature and pressure, and therefore vary as a function of altitude. The model used for this study assumes standard atmospheric properties fitted by spectral polynomials in the altitude.[4-39]

As has been mentioned previously, because of the complexity of the problem, it is virtually impossible to analyze all possible release locations and all possible particle sizes. However for standard conditions and the assumed particle size distribution of Figure 4-10, surface deposition densities can be computed for the most significant isotopes. Table 4-22 gives the results for a total release of material (5500 kg) at an altitude of 30 km and an injection latitude of 0° (Equator). Table 4-23 presents a similar analysis for a 45° N injection latitude. The information is presented as deposition densities ($\mu Ci/m^2$) and the Earth's surface area which would be affected by specific deposition densities. It can be seen that there would be very high radioactive waste concentrations in a small area (0.1 km^2) and the deposition density decreases as the area increases.

The total release of the waste material at high altitude would have serious consequences if conditions were such that injection occured over a populated land mass, and the material had characteristics such that the particle size distribution was as is given in Figure 4-10. More realistically, the probability of injection over a populated area must be considered as well as the likelihood that the material may break up into rather large fragments which might survive reentry. This would cause a small area of very high radioactive contamination.

4.4.2.3 Ecosystem Effects

The effect on ecosystems caused by a high altitude release of radioactive material from launch vehicle failure or reentry would be dominantly influenced by the (1) particle size distribution of material, (2) injection latitude and longitude, (3) the mix, and (4) deposition pattern across ecosystem types.

The types of effects which are possible are summarized in Section 4.4.1.4 and will not be repeated here. As described in 4.4.2.1 above, the region of release is considered to be 10–100 km above the surface. The following discussion is based on the assumption that complete burnup occurred during reentry and that no large portions of the nuclear waste material impacted the surface.

4.4.2.3.1 Acute Toxicity Effects

If post-accident particle sizes are large (see Section 4.4.2.2), then the major mode of exposure would be assimilation by ingestion. Depending upon the dispersion pattern, much of

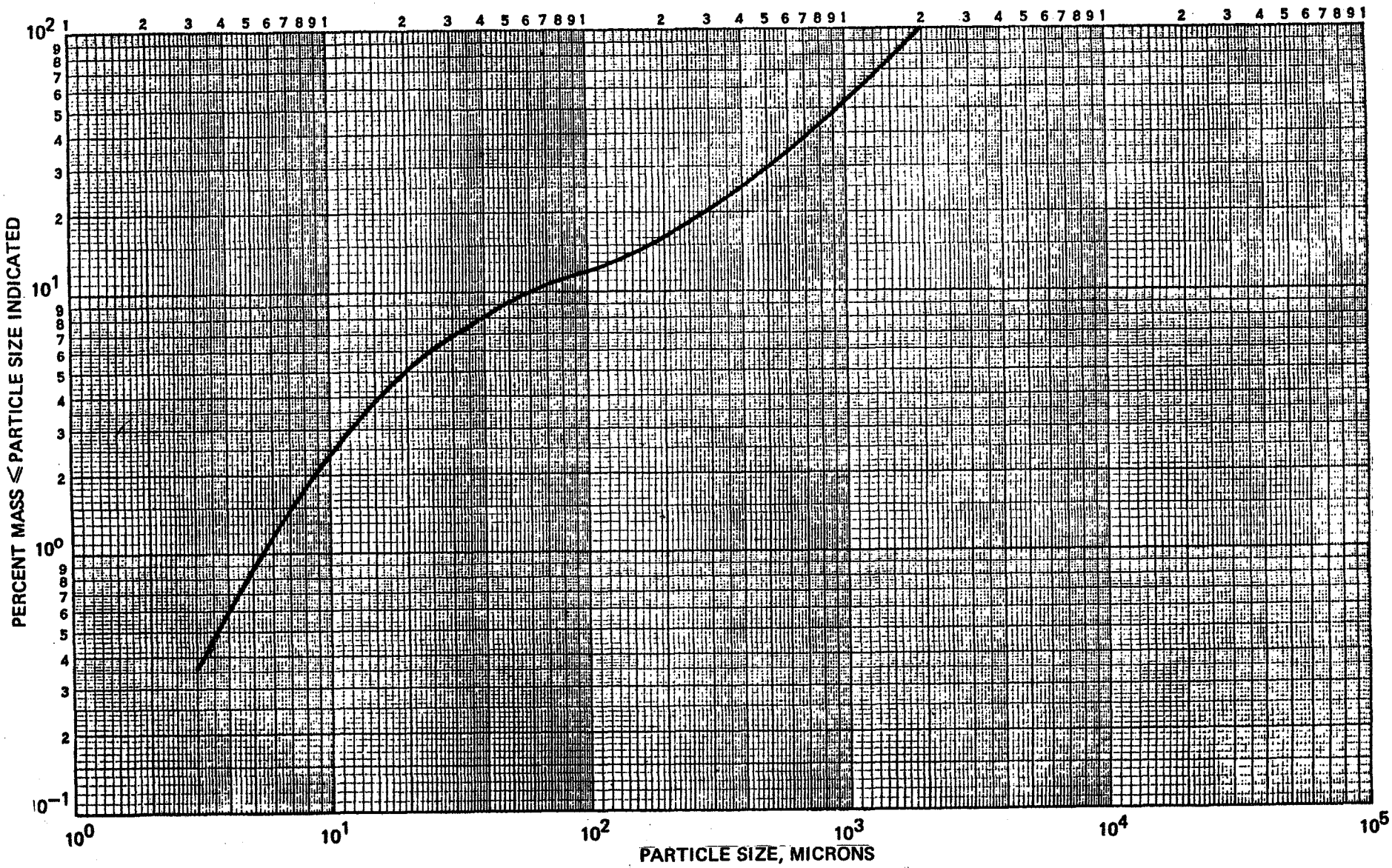


FIGURE 4-10. CUMULATIVE MASS DISTRIBUTION FOR PARTICLES LESS THAN OR EQUAL TO 2000 MICRONS (Fractured PUO_2 Fuel)

Source: Reference 4-39.

TABLE 4-22. FALLOUT OF RADIOACTIVE MATERIAL AT GROUND LEVEL ASSUMING: 30 KM RELEASE, PARTICLES 4-2000μ, AND 0° LATITUDE INJECTION[a]

	Mix No. 1						Mix No. 2					
			Deposition Density, μCi/m²						Deposition Density, μCi/m²			
Nuclide	Mass, kg	Activity, μCi	100 km²	10 km²	1 km²	0.1km²	Mass, kg	Activity, μCi	100 km²	10 km²	1 km²	0.1 km²
Curium 244	0.117	9.7E09[b]	2.1	68	1.9E03	8.7E03	2.33	1.9E11	3.8E01	1.3E03	3.3E04	1.8E05
Strontium 90	1.93	2.8E11	62	1960	5.6E04	2.5E05	38.3	5.5E12	1.1E03	3.9E04	9.6E05	4.8E06
Plutonium 238	5.34	9.3E10	20	651	1.9E4	8.4E04	106	1.8E12	3.6E02	1.3E04	3.2E05	1.6E06
Americium 241	0.25	8.1E08	0.2	5.7	1.6E02	7.3E02	4.97	1.6E10	3.2E00	1.1E02	2.8E03	1.4E04
Cesium 137	455	4.5E11	99	3150	9.0E04	4.1E05	90.2	8.9E12	1.8E03	6.2E04	1.6E06	7.8E06
Plutonium 241	306	3.5E11	77	2450	7.0E04	3.2E05	61.1	6.9E12	1.4E03	4.8E04	1.2E06	6.1E06
Americium 243	0.518	9.6E07	0.021	0.7	1.9E01	8.6E01	103	1.9E09	3.8E-01	1.3E01	3.3E02	1.7E03
Plutonium 240	21.1	4.8E09	1.1	34	9.6E02	4.3E03	420	9.5E10	1.9E01	6.7E02	1.7E04	8.4E04
Europium 154	0.150	2.2E10	4.8	154	4.4E03	2.0E04	2.97	4.3E11	8.6E01	3.0E03	7.5E04	3.8E05
Plutonium 237	24.6	1.5E09	0.3	10.5	3.0E02	1.4E03	490	3.0E10	6.0E00	2.1E02	5.3E03	2.6E04
Samarium 151	0.196	5.3E09	1.2	37.1	1.1E03	4.8E03	3.91	1.1E11	2.2E01	7.7E02	1.9E04	9.7E04
Subtotals			2.7E03	8.5E03	2.4E05	1.1E06			4.8E03	1.7E05	4.2E06	2.1E07

	Mix No. 3						Mix No. 4					
			Deposition Density, μCi/m²						Deposition Density, μCi/m²			
Nuclide	Mass, kg	Activity, μCi	100 km²	10 km²	1 km²	0.1 km²	Mass, kg	Activity, μCi	100 km²	10 km²	1 km²	0.1 km²
Curium 244	3.02	2.5E11	5.0E01	1.8E03	4.4E04	2.2E05	8.86	7.4E11	1.5E02	5.2E03	1.3E05	6.5E05
Strontium 90	49.7	7.2E12	1.4E03	5.0E04	1.3E06	6.3E06	0	0	0	0	0	0
Plutonium 238	0.687	1.2E10	2.4E00	8.4E01	2.1E03	1.1E04	0.402	7.0E09	1.4E00	4.9E01	1.2E03	6.2E03
Americium 241	6.44	2.1E10	4.2E00	1.8E02	3.7E03	1.9E04	18.9	6.1E10	1.2E01	4.3E02	1.1E04	5.4E04
Cesium 137	117	1.2E13	2.4E03	8.4E04	2.1E06	1.1E07	343	3.4E13	6.8E03	2.4E05	5.6E06	3.0E07
Plutonium 241	0.395	4.5E10	9.0E00	3.2E02	7.9E03	4.0E04	233	2.6E10	5.2E00	1.8E02	4.6E03	2.3E04
Americium 243	13.4	2.5E09	5.0E-01	1.8E01	4.4E02	2.2E03	39.1	7.2E09	1.4E00	5.0E01	1.3E03	6.3E03
Plutonium 240	2.72	6.2E08	1.2E-01	4.3E00	1.1E02	5.5E02	1.6	3.6E08	7.2E-02	2.5E00	6.3E01	3.2E02
Europium 154	3.85	5.6E11	1.1E02	3.9E03	9.8E04	4.9E05	11.3	1.6E12	3.2E02	1.1E04	2.8E05	1.4E06
Plutonium 237	3.18	2.0E08	4.0E02	1.4E00	4.9E01	2.5E02	1.86	1.1E08	2.2E-02	7.7E-01	1.9E01	9.7E01
Samarium 151	5.07	1.4E11	2.8E01	9.8E02	2.5E04	1.2E05	14.8	4.0E11	8.0E01	2.8E03	7.0E04	3.5E05
			4.3E03	1.4E05	3.6E06	1.8E07			7.6E03	2.6E05	6.1E06	3.2E07

(a) For Mix No. 5 (Tc-99) - Mass: 2547 kg
- Activity: 4.4E10 μCi
- Deposition Density: 100 km^2 - 8.8 $\mu Ci/m^2$
10 km^2 - 310 $\mu Ci/m^2$
1 km^2 - 7700 $\mu Ci/m^2$
0.1 km^2 - 39,000 $\mu Ci/m^2$

(b) 9.7E09 = 9.7×10^9.

TABLE 4-23. FALLOUT OF RADIOACTIVE MATERIAL AT GROUND LEVEL ASSUMING: 30 KM RELEASE, PARTICLES 4-2000μ, AND 45° LATITUDE INJECTION(a)

	Mix No. 1						Mix No. 2					
			Deposition Density, μCi/m²						Deposition Density, μCi/m²			
Nuclide	Mass, kg	Activity, μCi	100 km²	10 km²	1 km²	0.1 km²	Mass, kg	Activity, μCi	100 km²	10 km²	1 km²	0.1 km²
Curium 244	0.117	9.7E09(b)	8.1E00	1.6E02	1.1E03	2.0E03	2.33	1.9E11	1.6E02	3.0E02	2.1E04	4.0E04
Strontium 90	1.93	2.8E11	2.4E02	4.5E03	3.1E04	5.9E04	38.3	5.5E12	4.6E03	8.8E04	6.1E05	1.2E06
Plutonium 238	5.34	9.3E10	7.6E01	1.5E03	1.0E04	2.0E04	106	1.8E12	1.5E03	2.9E04	2.0E05	3.8E05
Americium 241	0.250	8.1E08	6.8E-01	1.3E01	8.9E01	1.7E02	4.97	1.6E10	1.3E01	2.6E02	1.8E03	3.4E03
Cesium 137	4.55	4.5E11	3.8E02	7.2E03	5.0E04	9.5E04	90.2	8.9E12	7.5E03	1.4E06	9.8E05	1.9E06
Plutonium 241	3.06	3.5E11	2.9E02	5.6E04	3.9E04	7.4E04	61.1	6.9E12	5.8E03	1.1E05	7.6E05	1.5E06
Amercium 243	0.518	9.6E07	8.1E02	1.6E00	1.1E01	2.0E01	103	1.9E09	1.6E00	3.0E01	2.1E02	4.0E02
Plutonium 240	21.1	4.8E09	4.0E00	7.7E01	5.3E02	1.0E03	420	9.5E10	8.0E01	1.5E03	1.0E04	2.0E04
Europium 154	0.150	2.2E10	1.8E01	3.5E02	2.4E03	4.6E03	2.97	4.3E11	3.6E02	6.9E03	4.7E04	9.0E04
Plutonium 237	24.6	1.5E09	1.3E00	2.4E01	1.7E02	3.2E02	490	3.0E10	2.5E01	4.8E02	3.3E03	6.3E03
Samarium 151	0.196	5.3E09	4.5E00	8.5E01	5.8E02	1.1E03	3.91	1.1E11	9.2E01	1.8E03	1.2E04	2.3E04
Subtotal			1.8E03	1.9E04	1.3E05	2.6E05			2.0E04	3.8E05	2.6E06	5.2E06

	Mix No. 3						Mix No. 4					
			Deposition Density, μCi/m²						Deposition Density, μCi/m²			
Nuclide	Mass, kg	Activity, μCi	100 km²	10 km²	1 km²	0.1 km²	Mass, kg	Activity, μCi	100 km²	10 km²	1 km²	0.1 km²
Curium 244	3.02	2.5E11	2.1E02	4.0E03	2.8E04	5.3E04	8.86	7.4E11	6.2E02	1.2E04	8.1E04	1.6E05
Strontium 90	49.7	7.2E12	6.0E03	1.2E05	7.9E05	1.5E06	0	0	0	0	0	0
Plutonium 238	0.687	1.2E10	1.0E01	1.9E02	1.3E03	2.5E03	0.402	7.0E09	5.9E00	1.1E02	7.7E02	1.5E03
Americium 241	6.44	2.1E10	1.8E01	3.4E02	2.3E03	4.4E03	18.9	6.1E10	5.1E01	9.8E02	6.7E03	1.3E04
Cesium 137	117	1.2E13	1.0E04	1.9E05	1.3E06	2.5E06	343	3.4E13	2.9E04	5.4E05	3.7E06	7.1E06
Plutonium 241	0.395	4.5E10	3.8E01	7.2E02	5.0E03	9.5E03	233	2.6E10	2.2E01	4.2E02	2.9E03	5.5E03
Americium 243	13.4	2.5E09	2.1E00	4.0E01	2.8E02	5.3E02	391	7.2E09	6.0E00	1.2E02	7.9E02	1.5E03
Plutonium 240	2.72	6.2E08	5.2E-01	9.9E00	6.8E01	1.3E02	16	3.6E08	3.0E-01	5.8E00	4.0E01	7.6E01
Europium 154	3.85	5.6E11	4.7E02	9.0E03	6.2E04	1.2E05	11.3	1.6E12	1.3E03	2.6E04	1.8E05	3.4E05
Plutonium 237	3.18	2.0E08	1.7E-01	4.5E00	2.2E01	4.2E01	1.86	1.1E08	9.2E-02	1.8E00	1.2E01	2.3E01
Samarium 151	5.07	1.4E11	1.2E02	2.2E03	1.5E04	2.9E04	14.8	4.0E11	3.4E02	6.4E03	4.4E04	8.4E04
Subtotal			1.7E04	3.3E05	2.2E06	4.2E06			3.1E04	5.8E05	4.0E06	7.7E06

(a) For Mix No. 5 (Tc-99) - Mass: 2547 kg
- Activity: 4.4E10 μCi
- Deposition: 100 km² - 37 μCi/m²
10 km² - 700 μCi/m²
1 km² - 4800 μCi/m²
0.1 km² - 9200 μCi/m²

(b) 9.7E09 = 9.7×10^9.

the nuclide load may settle to the surface rapidly, within a small, confined area. If this occurs, acute toxicities might be observed in some sensitive species. If they did, they would be similar to those described in Section 4.4.1.4, except the impacted systems would be different.

Injection of radioactive material at high altitude would allow almost any ecosystem of the Earth to be impacted. However, based on Figure 4-9, Northern hemisphere systems impacts would be greater with maximum deposition of small particle sizes at approximately 40° N latitude. The steepness with which acute toxicity would decline with distance would depend on the injection latitude. The greater the injection latitude, the greater the probability of local acute toxicity and the smaller the probability of even chronic exposure of systems not in the immediate area of influence. Predicted levels for total burnup would not be expected to increase acute toxicity effects significantly. However, if rapid fallout were to occur (see Section 4.4.2.2) acute effects would be severe within a localized area (see Tables 4-22 and 4-23).

4.4.2.3.2 Chronic Toxicity Effects

Deposition of all particle sizes from a high altitude release would most probably cause chronic toxicity effects on some ecosystem components. Tissue body burdens would generally increase and mutational damage could result in sensitive plant and animal populations. More indepth assessment of a high altitude burnup should include several scenarios with maximum depositions occurring in mid-northern latitudes and tropics-tundra areas as well as the relative isolation of impacted systems. The tropics and tundra are more sensitive to any stress than temperate latitude ecosystems. Chemical toxicity data would suggest that the same dose would cause a 3 to 5 times increase in effects, e.g., reproductive mortality.

While the quantitative assessment of chronic toxicity is outside the scope of this analysis, types of effects caused would be similar to those described in Section 4.4.1.4. A general decline in population survival or productivity over the impacted area is probable, although it would require sophisticated data collection and analysis to prove the effects had occurred.

4.4.2.3.3 Bioaccumulation

Without knowing the organismic composition of the impacted systems, good projections of bioaccumulation levels cannot be made. Process and mix importance would be similar to that detailed in Section 4.4.1.4.

The high altitude burnup might very well change the primary mechanism of bioaccumulation from assimilation to inhalation or absorption for a finite time period following the event.

From Tables 4-22 and 4-23, and referring again to Table 4-16, effects of at least Pu-238 and Pu-240 are anticipated. Both mammal and predatory fish will be affected and exhibit lower fecundity (reproductive viability) and higher genetic damage incidence than normal. Total nuclide exposure (Table 4-22) will be sufficiently high to cause increased disease incidence to exposed populations. Highest potential for bioaccumulation exists with Mix No. 3.

4.4.2.3.4 Ecosystem Process Disruption

If nuclide dispersion were large (e.g., >100 km^2), disruption of terrestrial ecosystem processes would be unlikely. Aquatic ecosystem processes would be doubly impacted since they receive not only depositional nuclides but those portions of deposits on terrain which are

mobilized by runoff, transport, or biological processes such as migration. The number of water bodies in the area impacted and relationship of their drainage basins to the contaminated area would determine exposure of aquatic biota and possibilities of aquatic ecosystem disruption. The effect of the five mixes would be qualitatively the same as that discussed in Section 4.4.1.4.

While the ecosystem process disruption of individual nuclides has not been studied, we would expect to see differences caused by the mix formulation. Mix No. 5, due to high mobility poses greater risks to aquatic ecosystem processes than to terrestrial. Mix Nos. 2 and 3 have greater bioaccumulation potentials than Mix No. 1, but are expected to have possibly less effect upon ecosystem processes, such as nutrient cycling.

4.4.2.4 Human Health and Safety

The high altitude release of radioactive material would potentially cause acute, chronic, and consumption effects on human populations. Particle size distributions, injection latitude, mix option, latitude and longitude of the release will determine the projected effect. See Section 4.4.2.1 for a discussion of these considerations.

4.4.2.4.1 Acute and Chronic Toxicity Effects

The following scenario was used to generate a case study of dose to human being tissue from a high altitude release. The maximum lung burden to individuals in the latitude of maximum integrated concentration is of interest and is obtained by use of the ICRP lung model.[4-35] The maximum lung burden is:

$$B_{ik} = \psi_{ik} L_{0.6}$$

where

B_{ik} = lung burden in equal area latitude band k due to waste release in injection latitude band i (μCi)

ψ_{ik} = integrated airborne concentration in each equal latitude band k due to waste release in injection latitude band i (μCi-sec/m^3)

$L_{0.6}$ = lung burden conversion factor of 6.8×10^{-5} μCi/μCi-sec/m^3 for a particle diameter of 0.6 micron.

The lung burden conversion factor, $L_{0.6}$, is obtained from Figure 4-11 where a particle size of 0.6 micron is assumed to obtain a realistic worst case estimate. Maximum lung burdens for each of the waste mixes are given in Table 4-24 for the two injection bands determined previously.

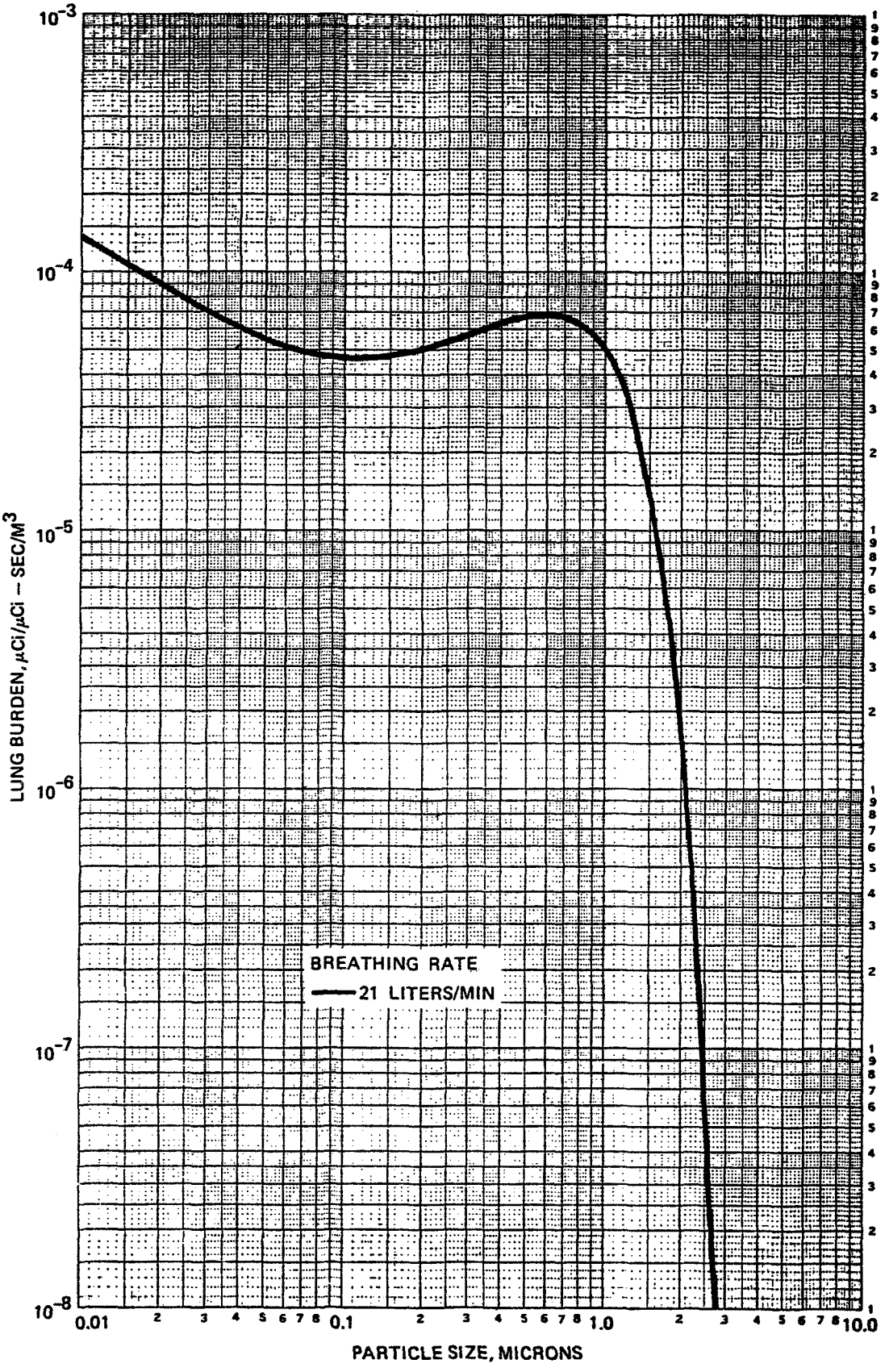


FIGURE 4-11. INITIAL LONG TERM LUNG BURDEN FROM INHALATION

Source: Reference 4-39.

TABLE 4-24. MAXIMUM LUNG BURDEN (μC_i) FOR INJECTION LATITUDES OF 0° AND 40°N[a]

Nuclide	Mix No. 1		Mix No. 2		Mix No. 3		Mix No. 4	
	0°	40°N	0°	40°N	0°	40°N	0°	40°N
Curium 244	8.8E-08[b]	2.2E-07	1.8E-06	4.4E-06	2.4E-06	5.8E-06	6.8E-06	1.7E-05
Strontium 90	2.7E-06	6.5E-06	5.2E-05	1.3E-04	6.7E-05	1.7E-04	0	0
Plutonium 238	8.8E-07	2.2E-06	1.7E-05	4.2E-05	1.2E-07	2.8E-07	6.5E-08	1.6E-07
Americium 241	7.5E-09	1.9E-08	1.5E-07	3.7E-07	2.0E-07	4.9E-07	5.7E-07	1.4E-06
Cesium 137	4.2E-06	1.0E-05	8.2E-05	2.1E-04	1.2E-04	2.8E-04	3.2E-04	7.9E-04
Plutonium 241	3.3E-06	8.2E-06	6.5E-05	1.6E-04	4.2E-07	1.0E-06	2.5E-07	6.1E-07
Americium 243	8.8E-10	2.2E-09	1.8E-08	4.4E-08	2.3E-08	5.8E-08	6.7E-08	1.7E-07
Plutonium 240	4.5E-08	1.1E-07	8.8E-07	2.2E-06	5.8E-09	1.4E-08	3.4E-09	8.2E-09
Europium 154	2.0E-07	5.2E-07	4.0E-06	1.0E-05	5.2E-06	1.3E-05	1.5E-05	3.7E-05
Plutonium 239	1.4E-08	3.5E-08	2.8E-07	6.8E-07	1.9E-09	4.7E-09	1.0E-09	2.6E-09
Neptunium 237	1.4E-11	3.5E-11	2.8E-10	1.0E-09	3.7E-10	8.8E-10	1.2E-09	2.8E-09
Curium 245	1.8E-11	4.4E-11	3.5E-10	8.8E-10	4.5E-10	1.1E-09	1.3E-09	3.3E-09
Samarium 151	5.0E-08	1.2E-07	1.0E-06	2.6E-06	1.3E-06	3.3E-06	3.7E-06	9.5E-06
Curium 246	3.5E-12	8.8E-12	6.8E-11	1.7E-10	9.5E-11	2.3E-10	2.7E-10	6.5E-10
Plutonium 242	6.7E-11	1.7E-10	1.3E-09	3.3E-09	8.8E-12	2.2E-11	5.2E-12	1.3E-11
Technetium 99	6.3E-10	1.6E-09	1.2E-08	3.1E-08	1.6E-08	3.9E-08	0	0
Tin 126	2.4E-11	6.1E-11	4.9E-10	1.2E-09	6.4E-10	1.6E-09	0	0
Selenium 79	1.7E-11	4.2E-11	3.4E-10	8.2E-10	4.5E-10	1.1E-09	0	0
Uranium 234	3.0E-11	7.5E-11	3.0E-12	4.5E-12	3.9E-12	9.5E-12	2.2E-12	5.6E-12
Zirconium 93	8.2E-11	2.0E-10	1.7E-09	4.2E-09	2.2E-09	5.4E-09	0	0
Uranium 238	1.4E-11	3.5E-11	1.4E-12	3.5E-12	1.8E-12	4.4E-12	1.0E-12	2.6E-12
Uranium 236	1.2E-12	3.1E-12	1.2E-13	3.1E-13	1.5E-13	3.7E-13	8.8E-14	2.4E-13
Palladium 107	5.2E-12	1.3E-11	1.0E-10	2.6E-10	1.3E-10	5.3E-10	0	0
Cesium 135	1.2E-11	3.1E-11	2.4E-10	6.1E-10	3.1E-10	7.5E-10	8.8E-10	2.2E-09
Uranium 235	6.4E-14	1.6E-13	6.4E-15	1.6E-14	8.2E-15	2.0E-14	4.8E-15	1.2E-14

(a) For Mix No. 5 (T_c-99) maximum lung burdens are: for 0° - 4.1E-07 μCi.
for 40°N - 1.0 x 10-6 μCi

(b) 8.8E-08 = 8.8×10^{-8} 1.0E-06.

By neglecting factors due to radioactive decay and daughter products, an approximation to the maximum lung dose rate can be computed based on the maximum lung burden[4-39]:

$$D = kEq/m$$

where

D = integrated dose to the lung (rem/year)

k = unit conversion constant = 51.2 × 365 = 18,688 dis-g-rem/μCi-year-MeV

E = effective energy transferred to organ (MeV/disintegration)

q = organ burden (μCi)

m = organ mass = 1000 grams for lung.

Values of the maximum lung dose rate are given in Table 4-25.

It can be seen from Table 4-25 that Mix No. 2 would present the greatest potential hazard with a summed dose of approximately .06 rem/year (40°N injection latitude) to the lung which can be compared to the recommended annual dose limits for individual members of the public of 1.5 rems/year for any single organ (excluding the red bone marrow, gonads, bone, thyroid, and skin). It must be recognized that the exposure levels calculated here can only be considered order of magnitude estimates; and, since the predicted exposures are only a factor of 25 below the recommended annual dose limits, a much more detailed analysis would be required to determine the potential radiation hazard from a major accident involving reentry and burnup.

The maximum burden and dose rate to the critical organ was also calculated for each of the considered isotopes and, generally is lower than the lung doses by approximately a factor of 10. This is still within the range of concern. For most of the considered isotopes, the critical organ is the bone and the recommended annual dose limits for individual members of the public are only 0.5 rem to the red bone marrow. Mixes No. 2, No. 3, and No. 4 should certainly be evaluated more closely. This is especially true since the net effect of reentry and burnup would be to raise the background radiation level over a large portion of the inhabited areas of the Earth.

At the dose levels which might occur from an accidental reentry and burnup of the waste material, there are no data for either animals or man which can be confidently applied to derive dose-effect relationships. The health effects (e.g., cancers) which might occur would probably be indistinguishable from nonradiation related effects and their incidence would be so low as to be essentially undetectable against the normal numbers of similar events.

4.4.2.4.2 Consumptive Effects

Long-term effects from high altitude release may primarily be through water, plant, and animal ingestion. The heterogeneity of the pattern created by small particle size release over a large area and human patterns of water and food consumption makes analysis of these effects difficult. In general, the greater the food productivity of the contaminated area, the greater potential for consumptive effects. This would be most likely for individuals using contaminated areas for all of their water and food consumption. Detectable effects might not be demonstrable for a period of two years after the event; however, further analysis is required if worldwide deposition (such as Table 4-21) of nuclides is assumed.

TABLE 4-25. MAXIMUM LUNG DOSE RATES (REM/YEAR)[a]

Nuclide	Mix No. 1		Mix No. 2		Mix No. 3		Mix No. 4	
	0°	40°N	0°	40°N	0°	40°N	0°	40°N
Curium 244	9.9x10-05[b]	2.5x10-04	2.0x10-03	4.9x10-03	2.7x10-03	6.5x10-03	7.6x10-03	1.9x10-02
Strontium 90	5.6x10-05	1.3x10-04	1.1x10-03	2.7x10-03	1.4x10-03	3.5x10-03	0	0
Plutonium 238	9.4x10-04	2.3x10-03	1.8x10-02	4.5x10-02	1.3x10-04	3.0x10-04	6.9x10-05	1.7x10-04
Americium 241	8.0x10-06	2.0x10-05	1.6x10-04	3.9x10-04	2.1x10-04	5.2x10-04	6.1x10-04	1.5x10-03
Cesium 137	3.2x10-05	7.7x10-05	6.3x10-04	1.6x10-03	9.2x10-04	2.1x10-03	2.5x10-03	6.1x10-03
Plutonium 241	3.3x10-06	8.1x10-06	6.4x10-05	1.6x10-04	4.2x10-07	9.9x10-07	2.5x10-07	6.0x10-07
Americium 243	8.9x10-07	2.2x10-06	1.8x10-05	4.4x10-05	2.3x10-05	5.8x10-05	6.7x10-05	1.7x10-07
Plutonium 240	4.5x10-05	1.1x10-04	8.8x10-04	2.2x10-03	5.8x10-06	1.4x10-05	3.4x10-06	8.1x10-06
Europium 154	3.2x10-06	8.4x10-06	6.4x10-05	1.6x10-04	8.4x10-05	2.1x10-04	2.4x10-04	5.9x10-04
Plutonium 239	1.4x10-05	3.5x10-05	2.8x10-04	6.8x10-04	1.9x10-06	4.7x10-06	1.0x10-06	2.6x10-06
Neptunium 237	1.3x10-08	3.2x10-08	2.6x10-07	9.2x10-07	3.4x10-07	8.1x10-07	1.1x10-06	2.6x10-06
Curium 245	1.8x10-08	4.4x10-08	3.5x10-07	8.8x10-07	4.5x10-07	1.1x10-06	1.3x10-06	3.3x10-06
Samarium 151	3.9x10-08	9.4x10-08	7.8x10-07	2.0x10-06	1.0x10-06	2.6x10-06	2.9x10-06	7.5x10-06
Curium 246	3.7x10-09	9.2x10-09	7.1x10-08	1.8x10-07	9.9x10-08	2.4x10-07	2.8x10-07	6.8x10-07
Plutonium 242	6.3x10-08	1.8x10-07	1.4x10-06	3.5x10-06	9.2x10-09	2.3x10-08	5.4x10-09	1.4x10-08
Technectium	1.2x10-09	3.1x10-09	2.3x10-08	6.0x10-08	3.1x10-08	7.5x10-08	0	0
Tin 126	4.3x10-10	1.1x10-09	8.8x10-09	2.2x10-08	1.1x10-08	2.9x10-09	0	0
Selenium 79	3.0x10-11	7.4x10-11	6.0x10-10	1.4x10-09	7.9x10-10	1.9x10-09	0	0
Uranium 234	2.7x10-08	6.9x10-08	2.7x10-09	4.1x10-09	3.6x10-09	8.7x10-09	2.0x10-09	5.1x10-09
Zirconium 93	3.1x10-11	7.5x10-11	6.4x10-10	1.6x10-09	8.2x10-10	2.0x10-09	0	0
Uranium 238	1.1x10-08	2.8x10-08	1.1x10-09	2.8x10-09	1.4x10-09	3.5x10-09	8.0x10-10	2.1x10-09
Uranium 236	1.1x10-09	2.7x10-09	1.1x10-10	2.7x10-10	1.3x10-10	3.2x10-10	7.7x10-11	2.1x10-10
Palladium 107	6.1x10-12	1.5x10-11	1.2x10-10	3.1x10-10	1.5x10-10	6.2x10-10	0	0
Cesium 135	1.5x10-11	3.8x10-11	3.0x10-10	7.5x10-10	3.8x10-10	9.2x10-10	1.1x10-09	2.7x10-09
Uranium 235	5.5x10-11	1.4x10-10	5.5x10-12	1.4x10-11	7.0x10-12	1.7x10-11	4.1x10-12	1.0x10-11
Σ Dose Rem/year	1.2x10-03	2.9x10-03	2.3x10-02	5.8x10-02	5.5x10-03	1.3x10-02	1.1x10-02	2.7x10-02

(a) For Mix No. 5 (T_c-99) maximum lung dose rates are: for 0° - 7.9x10-7 rem/year
for 40°N - 1.9x10-6 rem/year.

(b) 9.9 x 10-5 = 9.9 x 10^{-5}.

If fallout (e.g., Table 4-22) results, the primary modes of exposure from this event will be consumptive. The expected affected area would be greater than 100 km^2. High enough levels of nuclide deposition are expected to cause chronic health deterioration, and increased genetic damage through several generations (approximately 8 to 12 due to long nuclide half-lives).

4.4.3 Water Impact Resulting from Launch Vehicle Reentry of the Nuclear Waste Payload from Orbit (Major Impact to Ocean or Fresh Water)

In general, potential consequences of the release of the radioactive waste material in the ocean or in freshwater bodies are dependent upon the damage that the cocoon or container sustains in the accident. Two cases considered here are: (1) the loss in the water body of an undamaged container, and (2) the loss in the water body of a container damaged by fire and/or explosion (LV failure, reentry of cocoon, or terrestrial transport at sea). The process of release of radioactive material into water can occur in several ways. For example, in the case of a damaged container, the release may occur either over the water surface (fallout) or during the descent of the container through the water. The release from a fallout event would be very similar to the ones discussed in Sections 4.4.1.2 or 4.4.2.2. The release could also occur years after the loss of the container on the ocean floor (assuming no recovery). The time at which the material would begin to be released would depend upon the condition of the container and the type/condition of the ocean floor. On the other hand, the container may be damaged through hydrostatic pressure and corrosion. In the case where the package is buried in unconsolidated sediments, the container may fail as a result of high temperatures due to the low thermal conductivity of the sediments. In either of these cases the release would be delayed and slow. However, in a worst-case situation the package can suffer severe damage resulting in instantaneous release of all of the radioactive waste material. The transportation of this material to distances away from the location of the loss of container depends on the solubility of the various components contained.

For the purpose of this preliminary analysis, the transportation of the radioactive materials from a slow release source of nuclear waste payload deposited on the ocean floor is considered. The ecosystems effects caused by these materials and the ensuing impact on human health and safety are also discussed.

4.4.3.1 Water Quality

The impacts to water quality resulting from the release of radioactive materials lost in the ocean is studied in terms of concentration of the various nuclides in microcuries (μCi) per unit volume of water. The approach is based on the baseline assumptions stated in Section 4.4. The most significant of these assumptions is the worst-case scenario. The approach also assumes a simple analytical model describing the transportation and distribution of the radioactive material in the water surrounding the location of the loss of the waste.

The mathematical model used in the ensuing calculations is taken from Reference 4-39. This model which is known as the "Spreading Disc" Model assumes that the diffusion in the direction of the ambient current is negligible compared with the bulk flow.

The concentration C(μCi/cm^3) due to a given nuclide at a point (x,y,z) at time t is given by:

$$C(x,y,z,t) = \frac{Q(t)}{\pi\omega}\sqrt{\frac{U}{x^3 k_z}}\left[\text{Exp}\left\{-\frac{yU}{\omega x}-\frac{\lambda x}{U}\right\}\right]\left[\sum_{i=1}^{\infty}\text{Exp}-\frac{(z+N_i Z_b)^2 U}{4k_z x}\right]$$

where

- x = Direction of the current, cm
- z = Vertical direction, cm
- y = Perpendicular to x and z, cm
- $Q(t)$ = Fuel release source term as a function of time, μCi/sec
- ω = Diffusion velocity, cm/sec
- k_z = Vertical eddy diffusivity, cm^2/sec
- U = Mean current velocity, cm/sec
- λ = Radioactive decay constant, sec^{-1}
- Z_b = Upper diffusion boundary, cm
- i = Number of reflections from the upper boundary
- N_i = i–1 if i is odd
  = –i if i is even.

The source term Q is assumed to be a rectangular function of time, i.e.,

- Q = 0 for $t < x/U$
  = Q for $t \geq x/U$

The summation in the model is done up to i = 100. The difference from using any higher value (say 1000) is found to be insignificant.

Any numerical evaluation of this model requires a set of numerical values for the parameters describing the characteristics of the ocean. These parameters are ω, k_z, U, and Z_b. Two sets of values, one characterizing the intermediate layer of the ocean and the other characterizing the surface layer are used as lower and upper bound respectively. These values are presented in Table 4-26. A value of 200 meters assumed to be a representative value for the continental shelf area is used for Z_b. A further assumption is that both the surface and the bottom of the ocean are boundless planes.

The coordinate system x,y,z is centered at the position of the radioactive source. Since the transportation of the radioactive material is much faster along the direction of the current, the concentration is calculated at distances of 1, 10, 100, and 200 km in this direction. Further, the concentration is calculated at 3 different levels (z = 0 m, 100 m, 200 m) due to the vertical eddy diffusivity, k_z, being low relative to the current velocity, U.

TABLE 4-26. REPRESENTATIVE VALUES FOR AQUATIC DIFFUSION PARAMETERS

	Diffusion Velocity ω, cm/sec	Vertical Eddy Diffusivity k_z, cm^2/sec	Mean Current Velocity U, cm/sec
Surface layer (upper bound)	2.4	50	15
Intermediate layer (lower bound)	0.7	1.0	.01

The source term, Q in μCi/sec, is given by

$$Q = S\,R\,A$$

where

R = Dissolution rate, $\mu g/cm^2 sec$

S = Specific activity, $\mu Ci/\mu g$

A = Total surface area of activity, cm^2.

Let the diameter and length of a cylindrical container be d (cm) and if the dissolution activity is assumed to be confined only to a depth of τ cm from the surface, then the volume of the material involved in the dissolution activity would be

$$V = {}^3/_2\,\pi d^2\tau \qquad [{}^\pi/_4\,d^3] \quad .$$

The expression within the brackets would give the volume if the total waste material becomes released instantaneously. These alternate expressions will continue to be given in the ensuing derivation for the total surface area. The mass, M, of the material corresponding to V is given by

$$M = {}^3/_2\,\pi d^2\tau\rho \qquad [{}^\pi/_4\,d^3\rho]$$

where ρ is the density in g/cc. The mass of each particle is given by

$$m = {}^4/_3\,\pi r^3(\rho/0.65)$$

where r is the radius of a particle of material whose density is assumed to be $\rho/0.65$. Therefore, the number of particles released is $(5.85/8)\,(d^2\tau/r^3)\,[(1.95/16)(d^3/r^3)]$ whose surface area would be

$$A = (5.85/2)(\pi d^2\tau/r)\,[(1.95\pi/4)(d^3/r)] \quad .$$

The ratio of the surface areas under these alternate assumptions is approximately $6\tau/d$ which is about 1:200 if τ=0.1 cm and d=120.5 cm. The value of d has been obtained assuming that a payload of 5500 kg of waste material with a density of 4 gm/cc is contained in a cylindrical container of d (cm) diameter and d (cm) height. A summary of values of parameters required for the computation of surface area is given below:

Payload weight	5500 kg
Container diameter	120.5 cm
Depth of dissolution activity	0.1 cm
Size of particles (radius)	10^{-4} cm
Fuel density	4 g/cc

Data used in water dispersion calculations for the ten most hazardous nuclides are given in Table 4-27 for Mixes No. 2, No. 3 and No. 5. Since the solubility of the various isotopes of plutonium, americium, and curium are similar, the dissolution rate, R, for plutonium 238 found in the Reference 4-39 is used for these nuclides. All the other nuclides are very soluble and hence, the leach rate of $10^{-4} g/cm^2$ day of the total nuclear waste multiplied by the corresponding weight fraction of the nuclide in a given mix is used for their dissolution rate.

A simple computer program was developed to calculate the concentrations of the various nuclides in a given mix at different distances in the direction of the current. Altogether, 5 cases have been computed, as shown in Table 4-28 (by check marks). The results of these sample computations for concentrations are shown in Table 4-29. The concentrations are in $\mu Ci/m^3$.

TABLE 4-27. DATA ON TEN NUCLIDES USED IN CONCENTRATION COMPUTATION FOR A LOSS AT SEA

Nuclide	$t^{1/2}$(yr)	Dissolution Rate ($\mu g/cm^2$)	Specific Activity ($\mu Ci/\mu g$)	Weight Fraction Mix #2	Mix #3	Mix #5
Curium 244	17.6	1.25×10^{-7}	83.0	4.24×10^{-4}	5.49×10^{-4}	0.0
Strontium 90	27.7	0.697	144.0	6.97×10^{-3}	9.04×10^{-3}	0.0
Plutonium 238	86.4	1.25×10^{-7}	17.4	1.93×10^{-2}	1.25×10^{-4}	0.0
Americium 241	450.0	1.25×10^{-7}	3.24	9.03×10^{-4}	1.17×10^{-3}	0.0
Cesium 137	30.0	1.64	98.5	1.64×10^{-2}	2.13×10^{-2}	0.0
Plutonium 241	13.2	1.25×10^{-7}	113.0	1.11×10^{-2}	7.18×10^{-5}	0.0
Americium 243	7,950.0	1.25×10^{-7}	0.185	1.87×10^{-3}	2.43×10^{-3}	0.0
Plutonium 240	6,580.0	1.25×10^{-7}	0.227	7.63×10^{-2}	4.95×10^{-4}	0.0
Europium 154	16.0	0.0540	145.0	5.4×10^{-4}	7.0×10^{-4}	0.0
Technetium 99	212,000	1.42	0.0171	1.42×10^{-2}	1.84×10^{-2}	4.63×10^{-1}

TABLE 4-28. SAMPLE COMPUTATIONS PERFORMED FOR WATER QUALITY

z(m)	Mix #2	Mix #3	Mix #5
0.0 (bottom)	✓	✓	✓
100.0		✓	
200.0 (surface)		✓	

TABLE 4-29. WATER QUALITY PREDICTIONS FOR FIVE SAMPLE CALCULATIONS INVOLVING NUCLEAR WASTE MATERIAL RELEASE

Nuclide	Specific Activity, $\mu Ci/m^3$(a) Distance, km 1	10	100	200	1000	Distance, km 1	10	100	200	1000
	Mix No. 3, z = 0m					Mix No. 3, z = 100m				
Curium 244	2.0x10-08	6.4x10-10	2.0x10-11	7.2x10-12	1.0x10-12	0(b)	3.5x10-13	9.6x10-12	5.1x10-12	1.0x10-12
Strontium 90	3.2x10+00	1.0x10-01	3.2x10-03	1.1x10-03	1.6x10-04	0	5.6x10-05	1.5x10-03	8.2x10-04	1.6x10-04
Plutonium 238	9.6x10-10	3.0x10-11	9.6x10-13	3.4x10-13	4.9x10-14	0	1.7x10-14	4.6x10-13	2.5x10-13	4.9x10-14
Americium 241	1.7x10-09	5.3x10-11	1.7x10-12	6.0x10-13	8.6x10-14	0	2.9x10-14	8.0x10-13	4.3x10-13	8.6x10-14
Cesium 137	1.2x10+01	3.9x10-01	1.2x10-02	4.3x10-03	6.2x10-04	0	2.1x10-04	5.8x10-03	3.1x10-03	6.2x10-04
Plutonium 241	3.6x10-09	1.1x10-10	3.6x10-12	1.3x10-12	1.8x10-13	0	6.3x10-14	1.7x10-12	9.1x10-13	1.8x10-13
Americium 243	2.0x10-10	6.3x10-12	2.0x10-13	7.1x10-14	1.0x10-14	0	3.5x10-15	9.4x10-14	5.1x10-14	1.0x10-14
Plutonium 240	5.0x10-11	1.6x10-12	5.0x10-14	1.8x10-14	2.6x10-15	0	8.7x10-16	2.4x10-14	1.3x10-14	2.5x10-05
Europium 154	1.9x10-02	6.1x10-04	1.9x10-05	6.9x10-06	9.8x10-07	0	3.4x10-07	9.2x10-06	4.9x10-06	9.8x10-07
Technetium 99	1.6x10-03	5.0x10-05	1.6x10-06	5.6x10-07	8.1x10-08	0	2.8x10-08	7.5x10-07	4.0x10-07	8.1x10-08
	Mix No. 3, z = 200m					Mix No. 2, z = 0m				
Curium 244	0(b)	1.2x10-22	2.0x10-12	3.2x10-12	1.0x10-12	1.6x10-08	4.9x10-10	1.6x10-11	5.5x10-12	7.9x10-13
Strontium 90	0	1.9x10-14	3.2x10-04	5.1x10-04	1.6x10-04	2.5x10-00	7.8x10-02	2.5x10-03	8.8x10-05	1.3x10-04
Plutonium 238	0	5.7x10-24	9.6x10-14	1.5x10-13	4.9x10-14	1.5x10-07	4.7x10-09	1.5x10-10	5.3x10-11	7.6x10-12
Americium 241	0	9.9x10-24	1.7x10-13	2.7x10-13	8.6x10-14	1.3x10-09	4.1x10-11	1.3x10-12	4.6x10-13	6.6x10-14
Cesium 137	0	7.2x10-14	1.2x10-03	1.9x10-03	6.2x10-04	9.4x10-00	3.0x10-01	9.4x10-03	3.3x10-03	4.8x10-04
Plutonium 241	0	2.1x10-23	3.6x10-13	5.7x10-13	1.8x10-13	5.6x10-07	1.8x10-08	5.6x10-10	2.0x10-10	2.8x10-11
Americium 243	0	1.8x10-24	2.0x10-14	3.1x10-14	1.0x10-14	1.5x10-10	4.9x10-12	1.5x10-13	5.5x10-14	7.8x10-15
Plutonium 240	0	2.9x10-25	5.0x10-15	7.9x10-15	2.5x10-15	7.7x10-09	2.4x10-10	7.7x10-12	2.7x10-12	3.9x10-13
Europium 154	0	1.2x10-16	1.9x10-06	3.1x10-06	9.8x10-07	1.5x10-02	4.7x10-04	1.5x10-05	5.3x10-06	7.6x10-07
Technetium 99	0	9.4x10-18	1.6x10-07	2.5x10-07	8.1x10-08	1.2x10-03	3.9x10-05	1.2x10-06	4.3x10-07	6.3x10-08
	Mix No. 5, z = 0m									
Technetium 99	4.0x10-02	1.3x10-03	4.0x10-05	1.4x10-05	2.0x10-06					

(a) The time required to reach the equilibrium concentrations at the stated distances are: 111 minutes, ~19 hours, ~8 days, 15 days, and 77 days, respectively.

(b) Values smaller than 1x10-37.

Also given is the time in years, x/U, for reaching the equilibrium concentration at a particular point. As expected, the concentration decreases with distance and also with height above the ocean bottom. Since the vertical diffusivity is relatively slow compared with the current velocity, the concentration tapers off very fast with height near the source. However, this tapering levels off at about 100 km.

The concentration data shown in these tables assume that the dissolution activity is confined only to a depth of 1 mm on the surface of the container. If, on the other hand, instant dissolution is assumed, these concentrations must be multiplied by a factor of 200.

4.4.3.2 Ecosystem Effects

The effect of ocean or freshwater release of nuclides from terrestrial transport failure, launch vehicle failure, or reentry would be exclusively upon aquatic ecosystems, with minor exceptions (flooding causing deposition or tidal waves). Low production of biota in surface waters compared to terrestrial ecosystems, dilution, and water transport processes minimize impact to aquatic systems. It is assumed that less mobile nuclides, such as Pu and U would not remain in suspension but would be taken into biota via respiratory or assimilation processes, adsorbed to suspended solids, or be deposited onto sediments. The impact of release will be roughly inversely proportional to the size of the water bodies impacted.

4.4.3.2.1 Acute Toxicity Effects

If the recipient water body is small, such as a pond, first order stream, small estuary, or swamp, acute toxicity could occur. The greatest potential acute effects on biota will be those which could occur in slow flowing systems, such as ponds and small lakes, within the area of maximum nuclide deposition. If particle size distributions were such that most nuclides were in large fragments, sediments and their biotic communities would be targeted. Particles which would remain in suspension could furnish acute exposure to water column inhabitants. Water bodies not in the proximity of maximum deposition will not be susceptible to acute toxic exposures. Without more detailed assessment, the critical size of an impacted water body (defined as the size at which nuclide concentrations are below toxic levels) cannot be defined adequately. However, it is obvious that the threshold would be more likely to be approached the smaller the recipient water body. Acute toxicity occurring if the threshold were exceeded would be similar to those described in Section 4.4.1.4.

4.4.3.2.2 Chronic Toxicity Effects

Water bodies receiving direct deposition of nuclide wastes and small enough to allow only dilution factors of 1–2 million would display chronic toxicity effects. Particle size distribution would determine whether these effects would be predominantly in the water column or in sediments. The more mobile mixes, such as Mix No. 5, would be uniformly distributed and would equilibrate exposure to all biota contained in the system (not considering possible bioaccumulation pathways). Exposure of biota to less mobile nuclides would depend upon water pH, sediment resuspension rates, and water turnover rates.

Freshwater systems would be more susceptible to chronic effects from nuclide release. Marine systems are less affected because of tidal action dispersing nuclides, water ionic

strength, and low biotic productivities. In this initial assessment it is not possible to predict exposure of the various systems. Exposures exceeding chronic effects thresholds would produce observable changes as described in Section 4.4.1.4.

4.4.3.2.3 Bioaccumulation

In flowing water systems, such as streams or rivers, bioaccumulation to effects thresholds from nuclides released in a single accident is extremely unlikely. In sediment of those systems such processes might occur if sediment transport were negligible.

Accumulation in trophic chains could occur in small ponds or lakes impacted. If particle sizes of released nuclides were sufficiently small, phytoplankton-zooplankton-invertebrate-vertebrate biomagnification could occur. Mixes No. 2, No. 3, and No. 4 could be most damaging due to bioaccumulation of cesium and strontium. Since bioaccumulation of strontium is greater than cesium, Mix No. 3 would present the greatest risk.

4.4.3.2.4 Ecosystem Process Disruption

Aquatic ecosystem processes are regulated by consumer dynamics. If aquatic biota are damaged, especially top carnivores, nutrient cycling processes could be adversely affected. Primarily, this would lead to lower nutrient availability, minimized turnover, and ultimately, decreases in productivity.

As above, the larger the water body, the less the probability of effect. If processes were disrupted, the probabilities are high that water turnover would allow system recovery within 3–10 generations of the top carnivore of the system.

4.4.3.3 Human Health and Safety

The freshwater/marine release of wastes could potentially affect human health and safety. The major effect will be direct exposure in water supply contamination. Primary problems would be those associated with mixes high in technetium, strontium, and cesium. High absorption rates of many nuclides to suspended solids and to sediments reduce their risk.

Indirect exposure will primarily be by bioaccumulation of nuclides in aquatic food chains leading to man. Reduced productivity of aquatic organisms could limit food supplies to man.

4.4.4 Land Impact Resulting From Launch Vehicle Failure or Intact Reentry of the Nuclear Waste Payload

A major failure of the launch vehicle or failure of the parachute system on the reentry package could result in a land impact causing rupture of the cocoon and container holding the nuclear waste payload. The worst-case calculations would be for those assuming complete release of all of the material over the land area with some resuspension into the atmosphere. The following sections describe both air and land impacts followed by ecosystem and health and safety effects.

4.4.4.1 Air Quality

If we assume that the waste package will survive reentry and impact the ground essentially intact, depending on the impact surface, some or all of the waste material may be exposed to the environment. For this case there will not be as wide a dispersion as in the case for the high altitude release; however, if there are particles in the waste mix of 4 micron or less in diameter, a considerable local air quality impact might result. Assuming the particle size distribution of Figure 4-10 for the waste material, approximately 0.58% of the waste material will be in the respirable size range and can be locally transported after impact.

To provide a general basis for quickly assessing the release of inhalable material, an illustrative calculation has been made assuming: ground impact, Pasquill Stability Class F, no vertical inversion, wind speed of 4.5 m/sec, particle size distribution of Figure 4-10, and complete release of waste material to the environment. Under these conditions, the normalized total exposure ($\psi\bar{u}/Q$) as a function of downwind distance is shown in Figure 4-12[4-39]. From this plot and the fraction of waste below 4 micron diameter the integrated airborne concentration (μCi-sec/m^3) can be determined at various distances from the impact point. Table 4-30 gives the results for distances of 100, 1000, 10,000, 100,000 and 1,000,000 meters, respectively. The lung burden (μCi) and the lung dose (rem/year) are computed from these data and given in Tables 4-31 and 4-32, respectively.

From Figure 4-13 the downwind areas where the lung dose equals or exceeds the values given in Table 4-32 can be calculated and the results are given in Table 4-33. Effects on ecosystems and human health and safety are discussed in Sections 4.4.4.3 and 4.4.4.4, respectively.

4.4.4.2 Land Quality

If the waste package survives reentry and impacts intact the larger particles will not be dispersed widely and the land quality will not be immediately or directly affected beyond a few hundred to a few thousand meters. This, of course, is dependent on the impact surface, the wind speed, and the particle size distribution. The impact on land quality for a small area would be extreme and the area may have to be isolated for thousands of years. Again, the probabilities of this type of impact must be fully assessed before definite conclusions can be drawn, but even from a preliminary analysis, it is certain that the land quality for a relatively small area would be degraded to the point of uselessness and the area would be highly dangerous (lethal) for all forms of life. If an explosion would occur at impact, the resulting land quality insult would be similar to that discussed in Section 4.4.1.3.

To aid in assessment of the risk to land forms and/or populations, the worldwide distribution of surface soil types and data on the relationship between soil types and population densities are presented in Figures 4-6 and 4-14 and Tables 4-34 and 4-35.[4-39] Using the surface soil type data, the population data, and the desired orbital inclination, Olsen[4-39] has developed a computer code (POPDEN) which calculates cumulative reentry impact probability. Results for orbital inclinations of 10 and 40 degrees are given in Table 4-36.

The highest probabilities of impact occur for desert soil types at low population densities (Table 4-36) if the orbital inclination is 40 degrees. Characteristics of these soils make resuspension the major risk following the initial exposure risk. If the orbital inclination is 10°, then

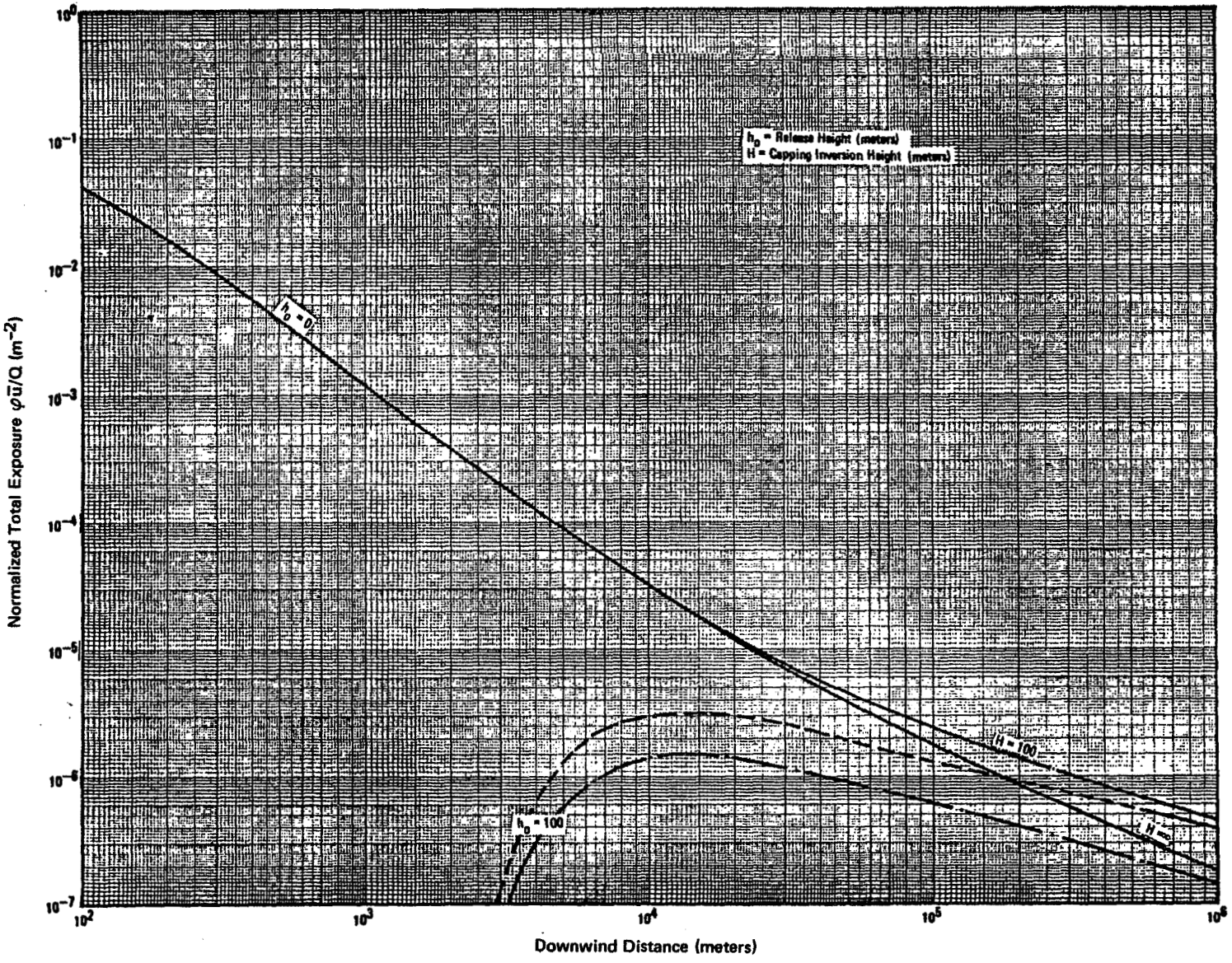


FIGURE 4-12. NORMALIZED TOTAL EXPOSURE FOR STABILITY REGIME F AS A FUNCTION OF DISTANCE

Source: Reference 4-39.

TABLE 4-30. INTEGRATED AIRBORNE CONCENTRATIONS OF NUCLIDES AS A RESULT OF LAND IMPACT AND RUPTURE OF COCOON

Nuclide	Mix No. 1 q' μCi	Q μCi	¥100	¥1,000	¥10,000	¥100,000	¥1,000,000	Mix No. 2 q' μCi	Q μCi	¥100	¥1,000	¥10,000	¥100,000	¥1,000,000
			μCi·sec/m³							μCi·sec/m³				
Cu 244	9.7E09	5.6E07	5.0E05	1.6E04	3.7E02	2.2E01	1.9E00	1.9E11	1.1E09	7.8E06	2.9E05	7.8E03	4.4E02	4.4E01
Sr 90	2.8E11	1.6E09	1.4E07	4.6E05	1.1E04	6.4E02	5.3E01	5.5E12	3.2E10	2.3E08	8.5E06	2.3E05	1.3E04	1.3E03
Pu 238	9.3E10	5.4E08	4.8E06	1.6E05	3.6E03	2.2E02	1.8E01	1.8E12	1.0E10	7.4E07	2.8E06	7.4E04	4.2E03	4.2E02
Am 241	8.1E08	4.7E06	4.2E04	1.4E03	3.1E01	1.9E00	1.6E-01	1.6E10	9.3E07	6.6E05	2.5E04	6.6E02	3.7E01	3.7E00
Cs 137	4.5E11	2.6E09	2.3E07	7.5E05	1.7E04	1.0E03	8.7E01	8.9E12	5.2E10	3.6E08	1.4E07	3.7E05	2.1E04	2.1E03
Pu 241	3.5E11	2.0E09	1.8E07	5.8E05	1.3E04	8.0E02	6.7E01	6.9E12	4.0E10	2.8E08	1.1E07	2.8E05	1.6E04	1.6E03
Am 243	9.6E07	5.6E05	5.0E03	1.6E02	3.7E00	2.2E-02	1.9E-02	1.9E09	1.1E07	7.8E04	2.9E03	7.8E01	4.4E00	4.4E-01
Pu 240	4.8E09	2.8E07	2.5E05	8.1E03	1.9E02	1.1E01	9.3E-01	9.5E10	5.5E08	3.9E06	1.5E05	3.9E03	2.2E02	2.2E01
Eu 154	2.2E10	1.3E08	1.2E06	3.8E04	8.7E02	5.2E01	4.3E00	4.3E11	2.5E09	1.8E07	6.6E05	1.8E04	1.0E03	1.0E02
Pu 239	1.5E09	8.7E06	7.7E04	2.5E03	5.8E01	3.5E00	2.9E-01	3.0E10	1.7E08	1.2E06	4.6E04	1.2E03	7.0E01	7.0E00
Sm 151	5.3E09	3.1E07	2.7E05	8.9E03	2.0E02	1.2E01	1.0E00	1.1E11	6.4E08	4.5E06	1.7E05	4.5E03	2.6E02	2.6E01
Subtotals		7.0E09	6.2E07	2.0E06	4.6E04	2.8E03	2.3E02		1.4E11	9.8E08	3.8E07	9.8E05	5.6E04	5.6E03

Nuclide	Mix No. 3 q' μCi	Q μCi	¥100	¥1,000	¥10,000	¥100,000	¥1,000,000	Mix No. 4 q' μCi	Q μCi	¥100	¥1,000	¥10,000	¥100,000	¥1,000,000
			μCi·sec/m³							μCi·sec/m³				
Cu 244	2.5E11	1.5E09	1.0E07	3.9E05	1.0E04	5.8E02	5.8E01	7.4E11	4.3E09	3.1E07	1.1E06	3.1E04	1.7E03	1.7E02
Sr 90	7.2E12	4.2E10	3.0E08	1.1E07	3.0E05	1.7E04	1.7E03	--						
Pu 238	1.2E10	7.0E07	4.9E05	1.9E04	4.9E02	2.8E01	2.8E00	7.0E09	4.1E07	2.9E05	1.1E04	2.9E02	1.6E01	1.6E00
Am 241	2.1E10	1.2E08	8.7E05	3.2E04	8.7E02	4.9E01	4.9E00	6.1E10	3.6E08	2.6E06	9.4E04	2.5E03	1.4E02	1.4E01
Cs 137	1.2E13	7.0E10	4.9E08	1.9E07	4.9E05	2.8E04	2.8E03	3.4E13	2.0E10	1.4E08	5.3E06	1.4E05	7.9E03	7.9E02
Pu 241	4.5E10	2.6E08	1.9E06	7.0E04	1.9E03	1.0E02	1.0E02	2.6E10	1.5E08	1.1E06	4.0E04	1.1E03	6.0E01	6.0E00
Am 243	2.5E09	1.5E07	1.0E05	3.9E03	1.0E02	5.8E00	5.8E-01	7.2E09	4.2E07	3.0E05	1.1E05	3.0E02	1.7E01	1.7E00
Pu 240	6.2E08	3.6E06	2.6E04	9.6E02	2.6E01	1.4E00	1.4E-01	3.6E08	2.1E06	1.5E04	5.6E02	1.5E01	8.4E-01	8.4E-02
Eu 154	5.6E11	3.3E09	2.3E07	8.7E05	2.3E04	1.3E03	1.3E02	1.6E12	9.3E09	6.6E07	2.5E06	6.6E04	3.7E03	3.7E02
Pu 239	2.0E08	1.2E06	8.2E03	3.1E02	8.2E00	4.6E-01	4.6E-02	1.1E08	6.4E05	4.5E03	1.7E02	4.5E00	2.6E-01	2.6E-02
Sm 151	1.4E11	8.1E08	5.8E06	2.2E05	5.8E03	3.3E02	3.3E01	4.0E11	2.3E09	1.6E07	6.2E05	1.6E04	9.3E02	9.3E01
Subtotals		1.2E11	8.4E08	3.2E07	8.3E05	4.7E04	4.7E03		3.6E10	2.6E08	9.8E06	2.6E05	1.5E04	1.5E03

Nuclide	Mix No. 5 q' μCi	Q μCi	¥100	¥1,000	¥10,000	¥100,000	¥1,000,000
			μCi·sec/m³				
Tc 99	4.4E10	2.6E08	1.8E06	6.8E04	1.8E03	1.0E02	1.0E02
	4.4E10	2.6E08	1.8E06	6.8E04	1.8E03	1.0E02	1.0E02

TABLE 4-31. LUNG BURDEN (μCi) AS A RESULT OF LAND IMPACT AND RUPTURE OF COCOON

Nuclide	Mix No. 1 Distance, m					Mix No. 2 Distance, m				
	100	1,000	10,000	100,000	1,000,000	100	1,000	10,000	100,000	1,000,000
Cu 244	3.4E01	1.1E00	2.5E-02	1.5E-03	1.3E-04	5.3E02	2.0E01	5.3E-01	3.0E-02	3.0E-03
Sr 90	9.5E02	3.1E01	7.5E-01	4.4E-02	3.6E-03	1.6E04	5.8E02	1.6E01	8.8E01	8.8E-02
Pu 238	3.3E02	1.1E01	2.5E-01	1.5E-02	1.2E-03	5.0E03	1.9E02	5.0E00	2.9E-01	2.9E-02
Am 241	2.9E00	9.5E-02	2.1E-03	1.3E-04	1.1E-05	4.5E01	1.7E00	4.5E02	2.5E-03	2.5E-04
Cs 137	1.6E03	5.1E01	1.2E00	6.8E-02	5.9E-03	2.4E04	9.5E02	2.5E01	1.4E00	1.4E-01
Pu 241	1.2E03	3.9E01	8.8E-01	5.4E-02	4.5E-03	1.9E04	7.5E02	1.9E01	1.1E00	1.1E-01
Am 243	3.4E-01	1.1E-02	2.5E-04	1.5E-06	1.3E-07	5.3E00	2.0E-01	5.3E-03	3.0E-04	3.0E-05
Pu 240	1.7E01	5.5E-01	1.3E-02	7.5E-04	6.3E-05	2.7E02	1.0E01	2.7E-01	1.5E-02	1.5E-03
Eu 154	8.2E01	2.6E00	5.9E-02	3.5E-04	2.9E-05	1.2E03	4.5E01	1.2E00	6.8E-02	6.8E-03
Pu 239	5.2E00	1.7E-01	3.9E-03	2.4E-04	2.0E-05	8.2E01	3.0E00	8.2E-02	4.8E-03	4.8E-04
Sm 151	1.8E01	6.1E-01	1.4E-02	8.2E-04	6.8E-05	3.1E02	1.2E01	3.1E-01	1.8E-02	1.8E-03

Nuclide	Mix No. 3 Distance, m					Mix No. 4 Distance, m				
	100	1,000	10,000	100,000	1,000,000	100	1,000	10,000	100,000	1,000,000
Cu 244	6.8E02	2.7E01	6.8E-01	3.9E-02	3.9E-03	2.1E03	7.5E01	2.1	1.2E-01	1.2E-02
Sr 90	2.0E04	7.5E02	2.0E01	1.2E00	1.2E-01	--	--	--	--	--
Pu 238	3.3E01	1.3E00	3.3E-02	1.9E-03	1.9E-04	2.0E01	7.5E-01	2.0E-02	1.1E-03	1.1E-04
Am 241	5.9E01	2.2E00	5.9E-02	3.3E-03	3.3E-04	1.8E02	6.4E00	1.8E-01	7.5E-03	7.5E-04
Cs 137	3.3E04	1.3E03	3.3E01	1.9E00	1.9E-01	9.5E03	3.6E02	9.5E00	5.4E-01	5.4E-02
Pu 241	1.3E02	4.8E00	1.3E-01	6.8E-03	6.8E-04	7.5E01	2.7E00	7.5E-02	4.1E-03	4.1E-04
Am 243	6.8E00	2.7E-01	6.8E-03	3.9E-04	3.9E-05	2.0E01	7.5E00	2.0E-02	1.2E-03	1.2E-04
Pu 240	1.8E00	6.5E-02	1.8E-03	9.5E-05	9.5E-06	1.0E00	3.8E-02	1.0E-03	5.7E-05	5.7E-06
Eu 154	1.6E03	5.9E01	1.6E00	8.8E-02	8.8E-03	4.5E03	1.7E02	4.5E00	2.5E-01	2.5E-02
Pu 239	5.6E-01	2.1E-02	5.6E-04	3.1E-05	3.1E-06	3.1E-01	1.2E-02	3.1E-04	1.8E-05	1.8E-06
Sm 151	3.9E02	1.5E01	3.9E-01	2.2E-02	2.2E-03	1.1E03	4.2E01	1.1E00	6.3E-02	6.3E-03

TABLE 4-32. LUNG DOSE (REM/YEAR) AS A RESULT OF LAND IMPACT AND RUPTURE OF COCOON

Nuclide	Mix No. 1 Distance, m 100	1,000	10,000	100,000	1,000,000	Mix No. 2 Distance, m 100	1,000	10,000	100,000	1,000,000
Cu 244	3.8E04	1.2E03	2.8E01	1.7E00	1.5E-01	5.9E05	2.2E04	5.9E02	3.4E01	3.4E00
Sr 90	1.9E04	6.0E02	2.9E00	8.9E-01	7.3E-02	3.2E05	1.2E04	3.3E02	1.8E01	1.8E00
Pu 238	3.4E05	1.2E04	2.7E02	1.6E01	1.3E00	5.4E06	2.0E05	5.4E03	3.1E02	3.1E01
Am 241	3.1E03	1.0E02	2.2E00	1.4E-01	1.2E-02	4.8E04	1.8E03	4.8E01	2.7E00	2.7E-01
Cs 137	1.2E04	3.9E02	9.2E00	5.2E-01	4.5E-02	1.8E05	7.3E03	1.8E02	1.1E01	1.1E00
Pu 241	1.2E03	3.9E01	8.7E-01	5.4E-02	4.5E-03	1.9E04	7.4E02	1.9E01	1.1E00	1.1E-01
Am 243	3.4E02	1.1E01	2.5E-01	1.5E-03	1.3E-04	5.3E03	2.0E02	5.3E00	3.0E-01	3.0E-02
Pu 240	1.7E04	5.5E-01	1.3E00	7.4E-02	6.2E-03	2.7E04	1.0E03	2.7E01	1.5E00	1.5E-01
Eu 154	1.3E03	4.2E01	9.5E-01	5.6E-03	4.7E-04	1.9E04	7.2E02	1.9E01	1.1E00	1.1E-01
Pu 239	5.2E02	1.7E-01	3.9E-01	2.4E-02	2.0E-03	8.1E03	3.1E02	8.1E00	4.8E-01	4.8E-02
Sm 151	1.4E01	4.8E-01	1.1E-02	6.4E-04	5.3E-05	2.4E02	9.4E00	2.4E-01	1.4E-02	1.4E-03
Subtotals	4.1E05	1.5E04	3.3E02	2.0E01	1.6E00	6.5E06	2.5E05	6.5E03	3.8E02	3.8E01

Nuclide	Mix No. 3 Distance, m 100	1,000	10,000	100,000	1,000,000	Mix No. 4 Distance, m 100	1,000	10,000	100,000	1,000,000
Cu 244	7.6E05	3.0E04	7.6E-02	4.4E01	4.4E00	2.4E06	8.4E04	2.4E03	1.3E02	1.3E01
Sr 90	4.1E05	1.5E-04	4.0E02	2.5E01	2.5E00	--	--	--	--	--
Pu 238	3.5E04	1.4E03	3.5E01	2.0E00	2.0E-01	2.1E04	8.0E02	2.1E01	1.2E00	1.2E-01
Am 241	6.3E04	2.4E-03	6.3E01	3.5E00	3.5E-01	1.9E05	6.8E03	1.9E02	8.0E00	8.0E-01
Cs 137	2.5E05	1.0E04	2.5E02	1.5E01	1.5E00	7.3E04	2.8E03	7.3E01	4.1E00	4.1E-01
Pu 241	1.3E02	4.8E00	1.3E-01	6.7E-03	6.7E-04	7.4E01	2.7E00	7.4E-02	4.1E-03	4.1E-04
Am 243	6.8E03	2.7E02	6.8E00	3.4E-01	3.4E-02	2.0E04	7.5E03	2.0E01	1.2E00	1.2E-01
Pu 240	1.8E02	6.4E00	1.8E-01	9.4E-03	9.4E-04	1.0E02	3.8E00	1.0E-01	5.7E-03	5.7E-04
Eu 154	2.6E04	9.5E02	2.6E01	1.4E00	1.4E-01	7.2E04	2.7E03	7.2E01	4.0E00	4.0E-01
Pu 239	5.6E01	2.0E02	5.6E-02	3.1E-03	3.1E-04	3.1E01	1.2E00	3.1E-02	1.8E-03	1.8E-04
Sm 151	3.1E02	1.2E01	3.1E-01	1.7E-02	1.7E-05	8.6E02	3.3E01	8.6E-01	4.9E-02	4.9E-02
Subtotals	1.5E06	5.0E04	1.5E03	8.2E01	8.1E00	2.8E06	1.1E05	2.8E03	1.5E02	1.4E01

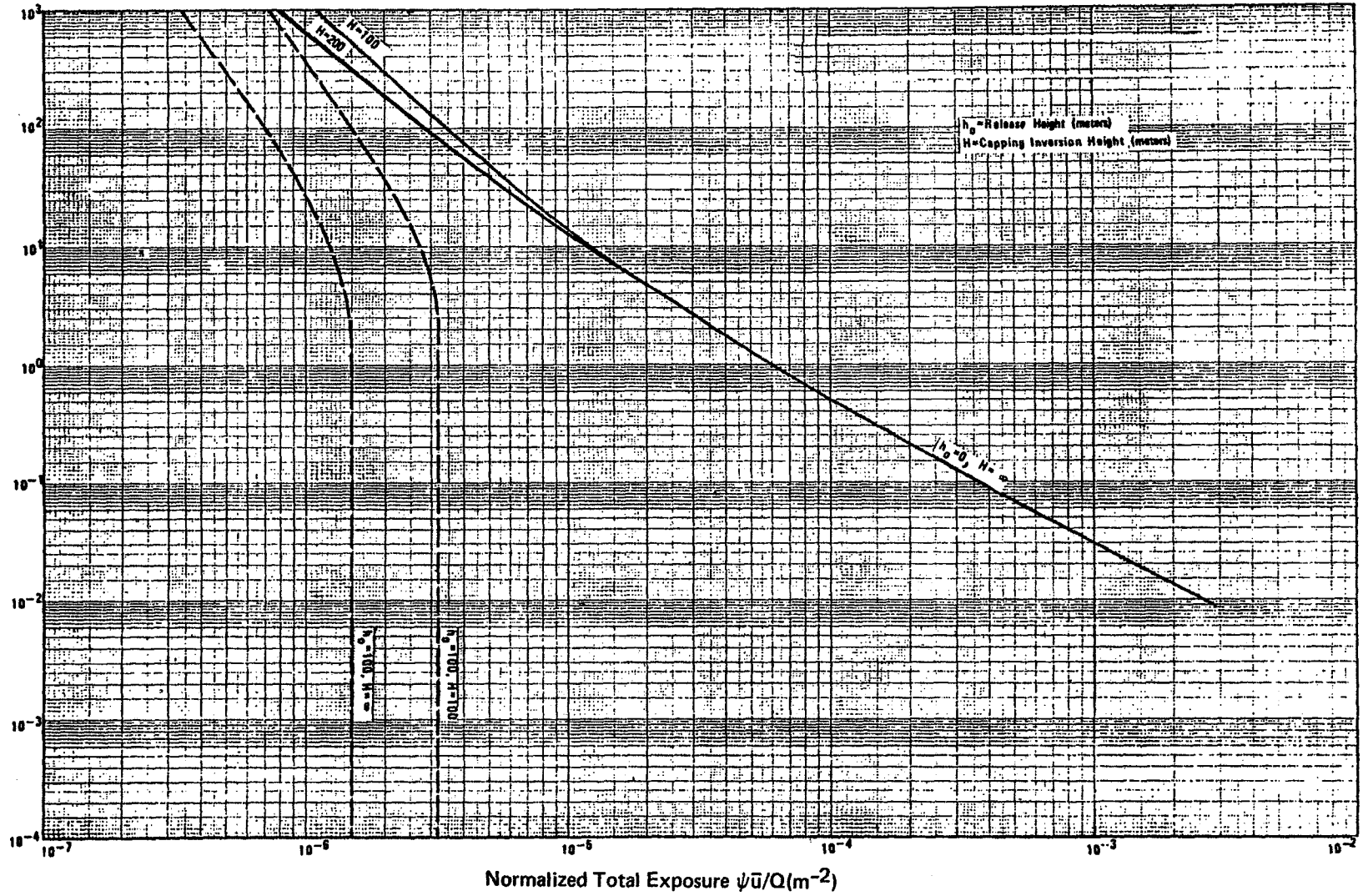


FIGURE 4-13. ISOPLETH AREA FOR STABILITY REGIME F AS A FUNCTION OF NORMALIZED TOTAL EXPOSURE

Source: Reference 4-39.

TABLE 4-33. DOWNWIND AREAS WHERE DOSE EQUALS OR EXCEEDS VALUES GIVEN IN TABLE 4-32

Distance, km	Mix No. 1			Mix No. 2			Mix No. 3		
	$\bar{u}/Q\ \Sigma\Psi$	A, m^2	Σ D, rems/year	$\bar{u}/Q\ \Sigma\Psi$	A, m^2	Σ D, rems/year	$\bar{u}/Q\ \Sigma\Psi$	A, m^2	Σ D, rems/year
1	1.3E-03	1.3E-02	1.5E04	1.2E-03	1.3E-02	2.5E05	1.2E-03	1.3E-02	5.0E04
10	3.0E-05	2.7	3.3E02	3.1E-05	2.7	6.5E03	3.2E-05	2.7	1.5E03
100	1.8E-06	2.5E02	2.0E01	1.8E-06	2.5E02	3.8E02	1.8E-06	2.5E02	8.2E01
1000	1.5E07	1.8E03	1.6	1.8E-07	1.8E03	3.8E01	1.8E-07	1.8E03	8.1

Distance, km	Mix No. 4			Mix No. 5		
	$\bar{u}/Q\ \Sigma\Psi$	A, m^2	Σ D, rems/year	$\bar{u}/Q\ \Psi$	A, m^2	D, rems/year
1	1.2E-03	1.3E-02	1.1E05	1.2E-03	1.3E-02	8.1
10	3.3E-05	2.7	2.8E03	3.1E-05	2.7	2.1E-01
100	1.9E-06	2.0E02	1.5E02	1.7E-06	2.7E02	1.2E-02
1000	1.9E-07	1.7E03	1.4E01	1.7E-07	1.8E03	1.2E-03

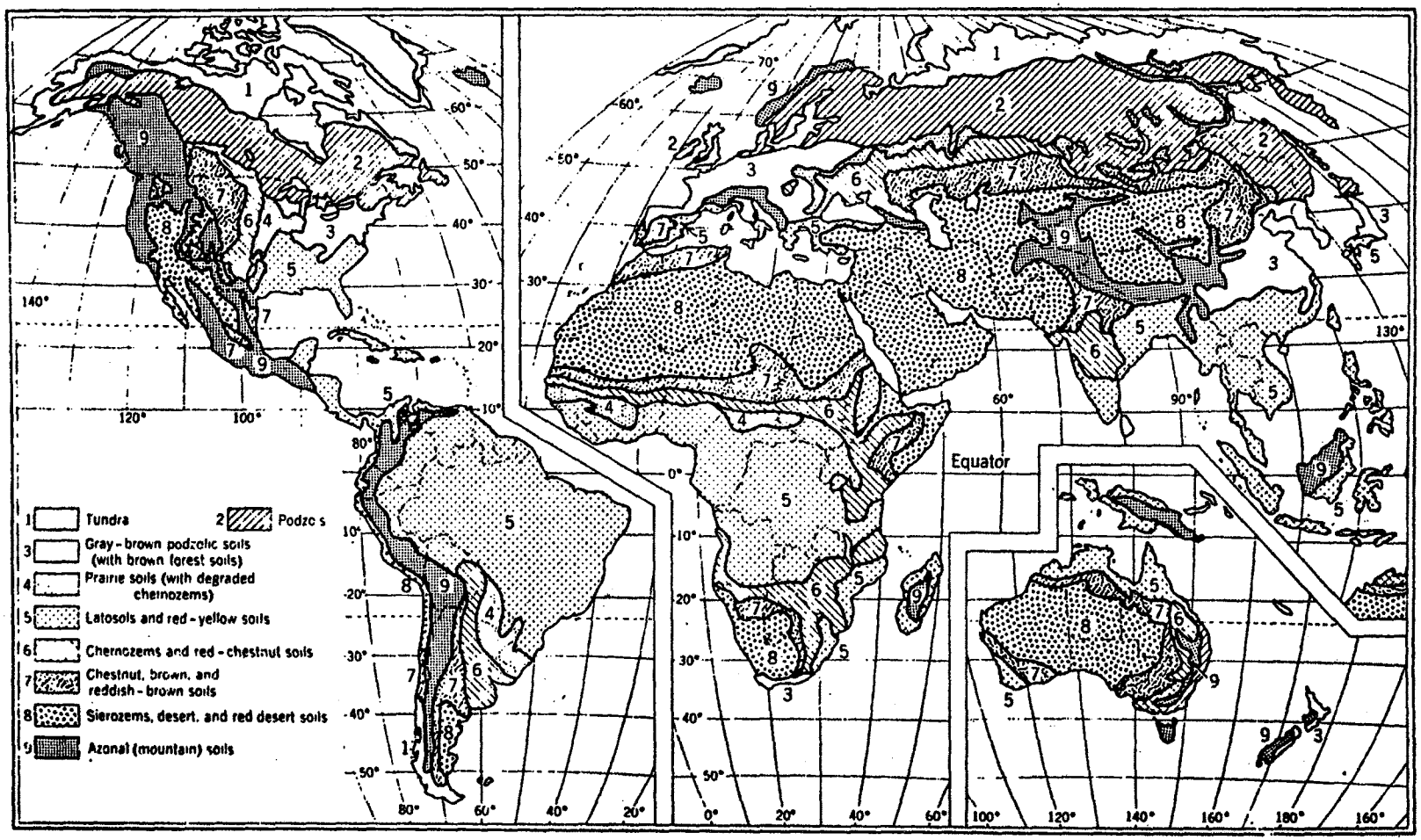

1 Tundra
2 Podzo s
3 Gray-brown podzolic soils (with brown forest soils)
4 Prairie soils (with degraded chernozems)
5 Latosols and red-yellow soils
6 Chernozems and red-chestnut soils
7 Chestnut, brown, and reddish-brown soils
8 Sierozems, desert, and red desert soils
9 Azonal (mountain) soils
Equator

FIGURE 4-14. WORLD DISTRIBUTION OF THE PRINCIPAL ZONAL SOIL GROUPS

Source: Reference 4-39.

TABLE 4-34. SOIL CLASSIFICATIONS AND DESCRIPTIONS

Type	Name	Description
1	Tundra	The tundra soils are included in the zonal soil groups of the humid climates. Tundra soils consist of mechanically broken rock particles, texturally clays, silts, and sands located on top of a perma-frost base. Various forms of ice wedges can be found in the finer-textured silts and clays.
2	Podzols	The podzols are associated with the sub-Arctic climate and northern parts of the humid continental climate areas. Podzols will also be found in Northern Europe and North America at the higher altitudes and lower temperatures.
3	Gray-brown podzolic (with brown forest soils)	This soil type resembles the podzols and is found in the less severe climates such as the northwestern United States and western and central Europe. Podzolic soils are usually associated with the deciduous forest, including such species as the maple, beech and oak.
4	Prairie soils (with degraded chernozems)	This type soil falls between the podzolic and chernozem soil belts of both North America and Europe. As the name implies, native vegetation is the prairie, an expanse of open grasslands.
5	Latosols and red-yellow soils	Latosols are found at the lower latitudes of the humid tropics. Latosols become hardened to a brick-like consistency after exposure to the atmosphere. Latosols contain valuable mineral deposits which accumulate near the surface.
6	Chernozems and red-chestnut	This soil, rich in humus, is usually found in the dryer climates. The top layer of this soil supports the grass and sod with a base consisting of a black layer of crumb or nut structure.
7	Chestnut, brown and reddish-brown	These soils are similar to the chernozems but have somewhat less humus. There is a sparser growth of grasses with the soil generally used for grazing land.
8	Sierozems, desert, and red desert	This type soil is characterized by a pale grayish or reddish color. There is a near absence of humus and consists mainly of a sandy texture.
9	Azonal (mountain)	The azonal soil is associated with stoney or thin mountain soils characteristic of those found on slopes too steep to permit profile development.

Source: Reference 4-39.

TABLE 4-35. PERCENT OF SOIL GROUP IN 6-DEGREE LATITUDE BANDS

LATITUDE BAND	WATER	PERCENT OF SOIL GROUP								
		1	2	3	4	5	6	7	8	9
-42,-36	95.95	0	0	0.20	0.07	0.26	0.78	1.56	0.46	0.72
-36,-30	90.96	0	0	0.16	0.48	0.97	1.94	3.07	1.45	0.97
-30,-24	79.19	0	0	0	1.45	2.18	3.39	2.66	9.68	1.45
-24,-18	76.88	0	0	0	1.16	6.94	4.05	2.31	7.22	1.44
-18,-12	79.12	0	0	0	0.52	13.05	4.44	0.52	0.78	1.57
-12,- 6	80.00	0	0	0	0.25	15.75	2.00	0	0.75	1.25
- 6, 0	77.39	0	0	0	0	19.25	1.53	0	0.61	1.22
0, 6	77.84	0	0	0	0.87	14.00	3.21	1.46	0.87	1.75
6, 12	77.69	0	0	0	0.94	10.69	3.14	2.83	3.77	0.94
12, 18	77.76	0	0	0	0.62	4.94	3.71	4.94	7.41	0.62
18, 24	73.14	0	0	0.34	0.34	4.13	2.07	2.41	15.50	2.07
24, 30	71.10	0	0	0.36	0	2.85	1.43	1.43	19.98	2.85
30, 36	72.53	0	0	1.32	0.66	2.98	1.32	2.98	14.24	3.97
36, 42	85.16	0	0.19	1.52	1.14	1.14	1.90	0.57	7.81	0.57

Soils Data Missing on 175 Centroids

Note: Negative Latitude Values Are South Latitudes

Source: Reference 4-39.

TABLE 4-36. CUMULATIVE IMPACT PROBABILITY AS A FUNCTION OF POPULATION DENSITY AND SOIL GROUP FOR RANDOM REENTRY FROM 10 AND 40 DEGREES INCLINATION ORBITS

POPULATION DENSITY LESS THAN OR EQUAL TO (/KM**2)	CUMULATIVE IMPACT PROBABILITY FOR SOIL GROUP (X100)									
	1	2	3	4	5	6	7	8	9	All Types
	10-Degree Orbital Inclination									
.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
.9	0.0	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	2.8
1.3	0.0	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	2.8
2.0	0.0	0.0	0.0	0.0	5.9	0.0	0.0	0.2	0.1	6.3
3.1	0.0	0.0	0.0	0.0	5.9	0.0	0.0	0.2	0.1	6.3
4.8	0.0	0.0	0.0	0.2	7.3	0.1	0.0	0.6	0.1	8.4
7.3	0.0	0.0	0.0	0.2	11.5	0.1	0.0	0.8	1.0	13.5
11.2	0.0	0.0	0.0	0.4	14.0	0.3	0.6	1.5	1.0	17.8
17.1	0.0	0.0	0.0	0.4	15.7	0.8	0.6	1.5	1.6	20.6
26.2	0.0	0.0	0.0	0.6	17.0	1.5	0.8	1.5	1.6	23.0
40.2	0.0	0.0	0.0	0.6	18.8	1.5	0.8	1.5	1.6	24.8
61.6	0.0	0.0	0.0	0.6	19.5	1.5	0.8	1.5	1.6	25.6
94.6	0.0	0.0	0.0	0.6	20.7	1.5	0.8	1.5	1.8	27.0
145.1	0.0	0.0	0.0	0.6	20.7	1.5	0.8	1.8	1.8	27.3
222.6	0.0	0.0	0.0	0.6	20.7	1.5	0.8	1.8	1.8	27.3
341.6	0.0	0.0	0.0	0.6	20.7	1.5	0.8	1.8	1.8	27.3
	40-Degree Orbital Inclination									
.1	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.5	0.0	0.7
.2	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.5	0.0	0.7
.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.8	0.0	1.0
.4	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.9	0.0	1.2
.6	0.0	0.0	0.0	0.0	0.0	0.1	0.3	1.0	0.0	1.4
.9	0.0	0.0	0.0	0.0	0.6	0.1	0.3	1.5	0.0	2.5
1.3	0.0	0.0	0.0	0.0	0.8	0.1	0.3	1.7	0.0	3.0
2.0	0.0	0.0	0.0	0.0	1.3	0.1	0.3	1.8	0.0	3.6
3.1	0.0	0.0	0.0	0.0	1.7	0.2	0.4	2.5	0.1	5.0
4.8	0.0	0.0	0.1	0.1	2.2	0.5	0.8	2.9	0.3	7.1
7.3	0.0	0.0	0.1	0.1	3.0	0.8	1.2	3.2	0.7	9.1
11.2	0.0	0.0	0.1	0.2	4.0	1.2	1.6	3.7	0.8	11.6
17.1	0.0	0.0	0.2	0.3	4.8	1.5	1.7	5.0	1.1	14.6
26.2	0.0	0.1	0.2	0.6	5.5	1.9	1.9	6.8	1.4	18.4
40.2	0.0	0.1	0.3	0.6	6.2	1.9	2.3	7.1	1.5	20.0
61.6	0.0	0.1	0.3	0.6	6.9	1.9	2.3	7.7	1.6	21.4
94.6	0.0	0.1	0.4	0.6	7.3	1.9	2.3	7.9	2.0	22.4
145.1	0.0	0.1	0.5	0.6	7.3	2.1	2.4	8.0	2.0	23.0
222.6	0.0	0.1	0.6	0.6	7.7	2.1	2.5	8.0	2.1	23.6
341.6	0.0	0.1	0.6	0.6	7.7	2.1	2.5	8.0	2.1	23.6

Source: Reference 4-39.

Note: See Table 4-34 and Figure 4-14 for soil group definition.

latasol (soil type 5) would have the highest probability of impact. The population density on this soil type is greater. Latasol soils are important to further assessment of chronic and consumptive risks because (1) they are the major agricultural soils and (2) they are more highly populated than other soil types.

4.4.4.3 Ecosystem Effects

The effects of land releases of radioactive material upon impact following launch vehicle or reentry system failure will be primarily of local significance. Significant nuclide concentrations would be found at least within a distance of from 1 to 1000 km of the impact point. Inhalation threats would be predictable from particle size distributions of nuclides released upon impact. Data in Table 4-33 suggest this event might be more risky than a catastrophic failure. While the calculations show the risk higher than exposure from a catastrophic failure, it seems that the underlying assumption may have led to this circumstance. In reality, effects from this event are expected to be less than that predicted and less than that of a catastrophic on-pad failure.

This case is similar to that of the local radionuclide releases described in Section 4.4.1.4. The land impacted by the event would determine the deviations from that case. Since approximately 30 percent of the Earth's land is desert, only minimal effects are expected in these areas. The only land systems which could be sources of other problems, such as extreme economic losses and the threatening of human health, would be agricultural systems in temperate latitudes.

4.4.4.4 Human Health and Safety

The danger of exposure of human populations is a function of (1) probability of land-soil impact (Figure 4-15), and (2) population density and distribution in the affected area (Figure 4-16). While the impact probability for land increases slightly as a function of orbital inclination, soil impact probability declines. The local population density as a function of orbital inclination is given in Figure 4-16. The least risk to man would result from an intact reentry upon land from orbital inclinations of ~0°. A launch site located on the Equator would provide minimal risks to man. The greater the inclination of the orbit, the greater the safety hazard for a finite area which might have high population densities.

Acute exposure of human populations especially in urban areas would pose the single most important impact from an on-land accident. Chronic effects which might be experienced are described in Section 4.4.1.5.

4.4.5 Impacts Caused by Anomalous Events at Space Destinations

Anomalous events in space which could result in the release of nuclear waste and the consequences of such releases should they occur are considered in this section. In most cases, the hazards to the terrestrial biosphere would be small because of the great separation distances that are involved. A possible exception is the case of storage of wastes in high Earth orbit where the separation distances are not great. Also, in most cases, the hazards to the local space environment if accidental release should occur would be small because most regions of space will never be traversed by life forms.

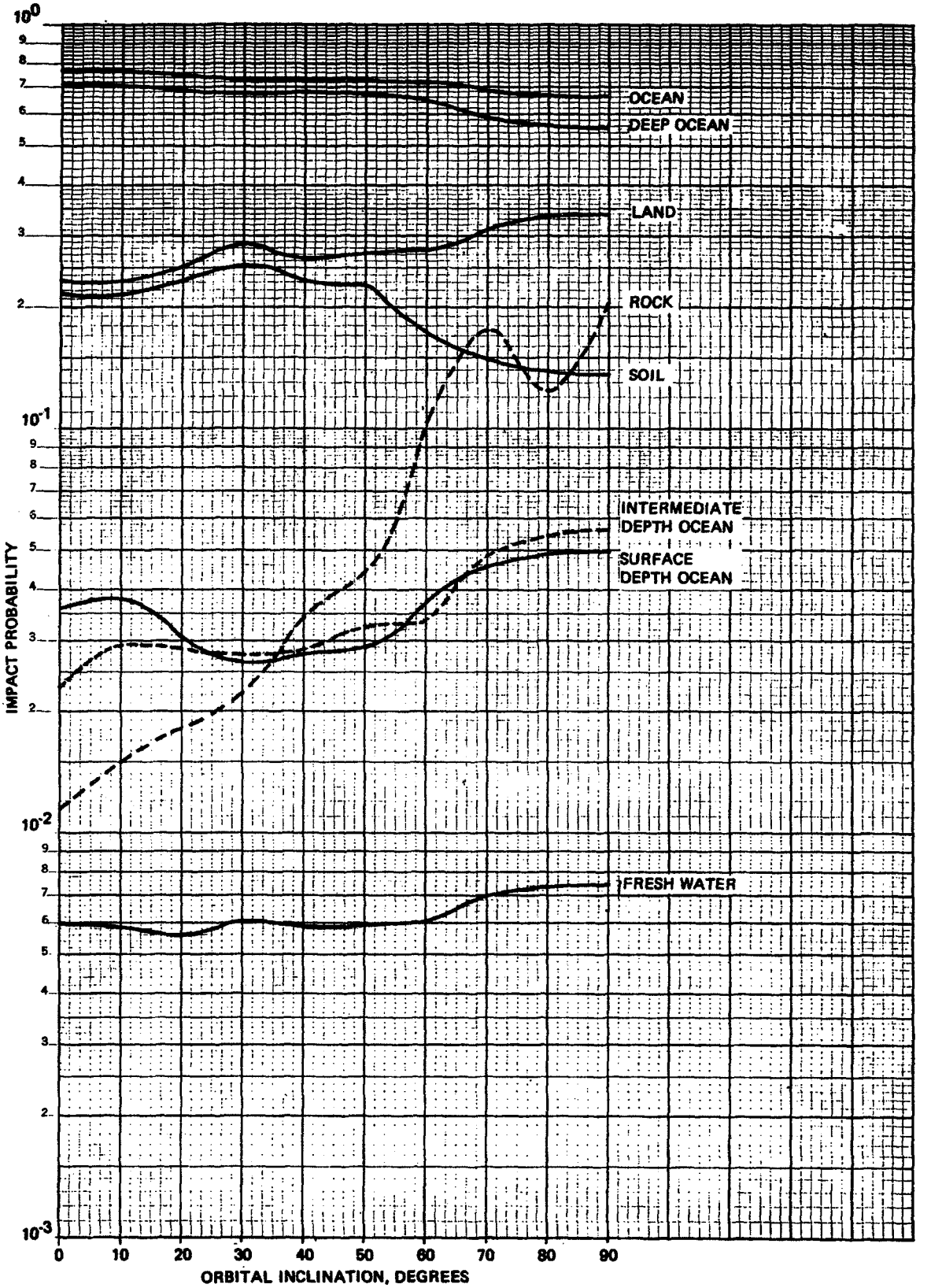


FIGURE 4-15. RANDOM ORBITAL REENTRY IMPACT PROBABILITIES

Source: Reference 4-39.

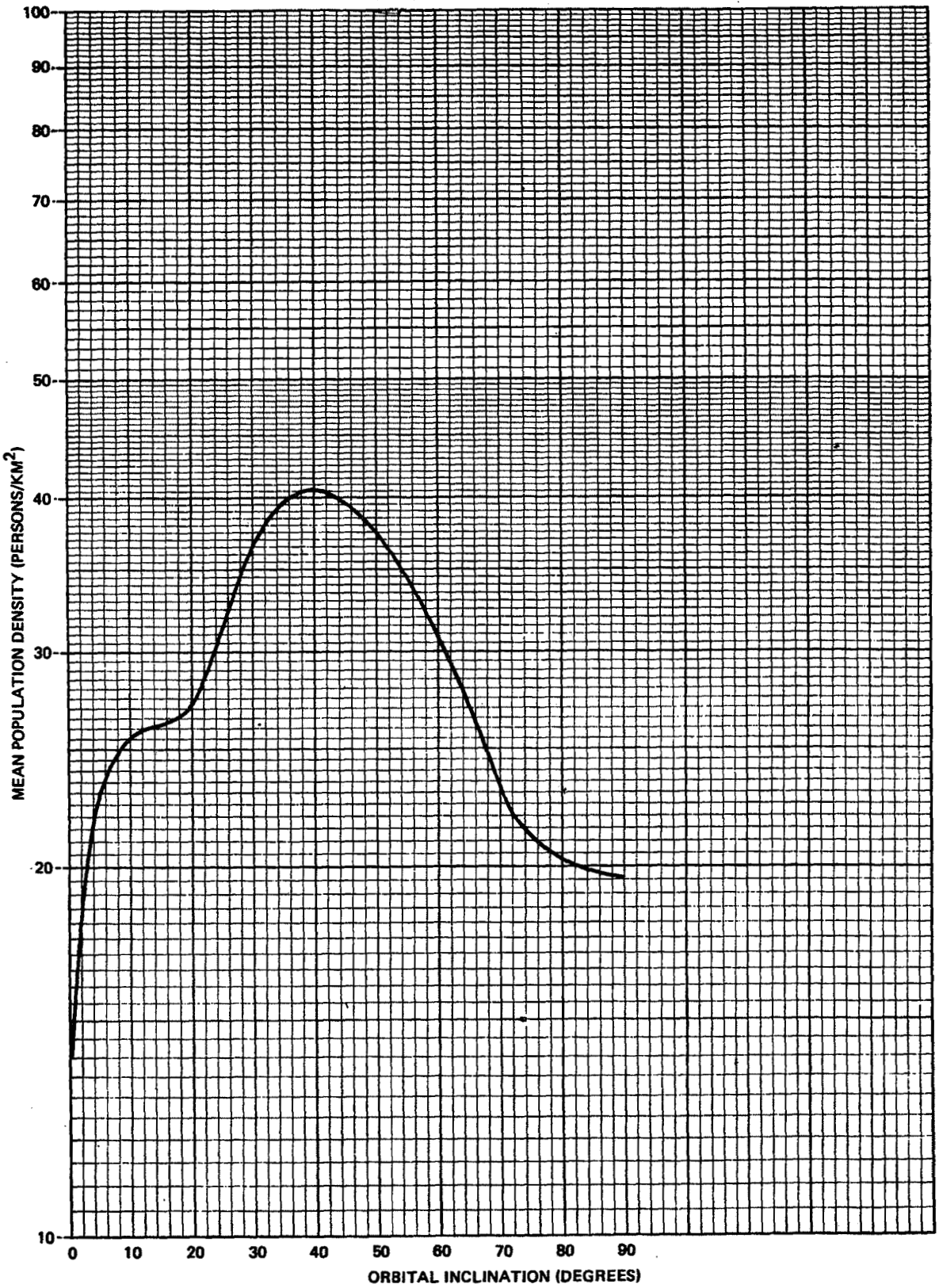


FIGURE 4-16. EXPECTED POPULATION DENSITY IMPACTED VERSUS ORBITAL INCLINATION (LAND IMPACT PROBABILITY = 1.0)

Source: Reference 4-39.

4.4.5.1 Earth Orbit Contamination

The placement of nuclear waste canisters in high Earth orbits requires a velocity impulse maneuver at the storage orbit altitude (apogee impulse) in addition to the velocity impulse provided at low Earth orbit (perigee impulse) provided by the OTV (OTV assumed to be chemical system).

Table 4-37 shows the performance statistics for expendable chemical propulsive stages used on both manned and unmanned flights. In addition, two planned upper stages—the Interim Upper Stage (IUS) and the Tug—are included in the table. The reliability record for the man-rated systems are highest; however, these systems have had relatively limited flight histories. The more extensively used upper stages for automated spacecraft have success ratios ranging from 0.88 to 0.97 for liquid propellant stages, and from 0.97 to 0.99 for solid propellant stages. A considerable number of the failures of these stages were propulsion failures; but, many were noncatastrophic wherein the propulsion system failed to ignite.

The failure of the apogee propulsion system, no matter what type (solid or liquid), constitutes a major hazard which could result in the release of the nuclear waste and its introduction into the Earth biosphere. If the propulsion system fails to ignite, the nuclear waste canister would remain in a highly elliptical orbit with its perigee at the Space Shuttle parking orbit altitude. Gradually, it would decay toward a circular orbit at that altitude and then reenter the Earth atmosphere. The length of time required for the decay of a highly elliptical orbit depends in the first order on the perigee altitude and in the second order on the ballistic coefficient and the orientation of the orbit. If the perigee altitude is 250 km or greater and the apogee altitude is on the order of 1×10^5 km, the lifetime is estimated to be much greater than 5000 years.[4-42]

Another serious hazard is the danger of collisions between the waste canisiter and satellites or debris which exist in Earth orbits at virtually all altitudes and inclinations; but concentrated mainly in the region below a few thousand kilometers altitude. The highly elliptical orbit of an "uncircularized" waste canister would cause it to pass frequently through the region where collisions are most likely to occur. The probability of a collision between objects in space depends on their orbits, the overall population of satellites and debris as a function of time, their spatial distribution and the sizes of the objects. Satellite collision probabilities have been estimated for a large satellite(~50 m diameter)in a circular orbit at 500 km altitude and 55 degree inclination.[4-43] The total collision probability for a ten year mission was estimated to be as high as 0.04. The collision probability for a nuclear waste canister at this altitude would be much less because of the much smaller collision cross section. For example, the collision probability for a waste canister might be several orders of magnitude less than that of a large space station; but, even so, it is not likely to be much less than the order of 10^{-3} or 10^{-4} per year. If so, at least one collision is likely to occur during the orbit lifetime of a canister in a highly elliptical orbit.

If a collision did occur, it might have a beneficial effect of allowing the waste material to disperse and so avoid an intact reentry and a concentrated release in the upper atmosphere. However, at the same time, it would have the detrimental effect of precluding the possibility of a future attempt to recapture and retrieve the canister before it reenters.

TABLE 4-37. UPPER STAGE RELIABILITY

Upper Stage	No. of Opportunities[a]	No. of Successes	Success Ratio
Solid Propellant			
Anteres (Scout)	70	69	0.99
Altair (Scout)	70	69	0.99
TE-364 (Delta, Centaur)	32	31	0.97
IUS (Planned)	—	—	0.99
Liquid Propellant			
Non-Cryogenic			
Delta (Thor)	118	115	0.97
Transtage (Titan)	25	22	0.88
Agena (Thor, Atlas, Titan)	207	192	0.93
CSM (Apollo)	16	15[b]	0.94
LEM Descent (Apollo)	9	9	1.00
LEM Ascent (Apollo)	9	9	1.00
Cryogenic			
Centaur (Atlas, Titan)	35	31	0.89
S-IVB (Saturn)	18	18	1.00
Tug (Planned)	—	—	0.99

Notes: (a) Operational flights only based on Reference 4-41.
(b) One failure attributed not to propulsion system or guidance system — but to power/life support system failure (Apollo 13).

4.4.5.2 Lunar Surface Contamination

Similar to the case of high Earth orbits, lunar storage/disposal options would require terminal propulsion. A soft landing on the lunar surface can be performed directly (as Surveyor) requiring one propulsion burn or by way of an intermediate lunar orbit (as Apollo) requiring two propulsion burns. Precision guidance and control systems would be required and the entire OTV must be highly reliable.

The possible adverse consequences of propulsion, guidance or control anomalies include: (1) uncontrolled hard landing on the lunar surface and (2) lunar fly-by with the possibility of reencountering the Earth. The targeting of the waste canisters as they are propelled out of Earth orbit has direct influence on which of these two possibilities is the more likely. If the prevention of accidental contaimination of the Moon is a primary concern, it is likely that the targeting philosophy would be to select a lunar fly-by, Earth escape trajectory as the contingency. In case of a failure or malfunction, the waste canister would proceed onto a heliocentric orbit not far removed from that of the Earth. Consequently, there would remain some very small possibility of a future reencounter with the Earth.

Uncontrolled hard landings on the lunar surface as a result of propulsion or guidance malfunctions could result in impacts at velocities of at least 2.4 km/sec. This would produce a crater about 10 m in diameter and could scatter debris—including the 5500 kg of nuclear waste—over an area approximately one kilometer in diameter. Such an event would probably preclude the future use of that area and natural resources for millions of years.

4.4.5.3 Heliocentric and Solar System Escape Trajectories

Trajectories that would carry the nuclear wastes far away from the Earth, either toward or away from the sun or out of the solar system, appear to have the lowest probabilities of adversely affecting other celestial bodies or orbital regions. There would remain a very small possibility that a failure of the canister and subsequent release of the nuclear waste could occur. The possible consequence of such a release is described next for the cases of a heliocentric trajectory toward the sun, a heliocentric trajectory away from the sun and a solar system escape trajectory.

If nuclear waste were released in helocentric orbit somewhere inside that of the Earth's orbit, the action of the solar wind and solar pressure would tend to disperse it and to drive it outward towards the Earth. The spatial concentration, however, would be quite small.

The release of nuclear waste in regions of space outside the solar system would not produce any detectable impact upon other celestial bodies. The distances to other planetary systems (outside our solar system) are so large that any premature release of nuclear waste would disperse (or decay) to insignificant levels before any detrimental effects might occur.

4.5 Suggested Design and Operational Procedure Criteria and Improvements

Various design and operations criteria and improvements are suggested, such that the worst-case events, as defined in Section 4.4, can be avoided or prevented. They are as follows:

Waste

- The waste should be in a solid form such that it is not easily dispersible under the various physical environments possible. This provides for recovery of the material and reduces impacts to large areas and populations.

Container Systems

- During all phases of the disposal mission, if it is possible for the waste payload to reenter the Earth's biosphere, a "cocoon" capable of surviving atmospheric reentry and land and sea impact is recommended. In addition to the reentry cocoon perhaps a modest container system could be devised, such that, after the OTV's guidance system has projected that the vehicle will have a high probability of mission success, the OTV carried, protective shielding could be jettisoned, thus providing the required degree of performance for a reasonably small penalty. This protective shielding would be designed only for reentry survival.
- For a lunar disposal/storage disposal concept the container's passive thermal system should be designed such that thermal limits would not be reached, if buried in the lunar surface.
- If waste container is lost at sea as a result of shipping or flight accident, the container should survive the high hydrostatic pressure and survive high temperatures that might be experienced if buried in sediment.
- Depending upon which disposal concept is chosen, consideration should be given to container design, such that it can survive, for many thousands of years, the solar wind, solar radiation, and micrometeorite environment in space.
- The reentry container (cocoon) should be equipped with a radio transmitter and a flotation device.

OTV System

- The chemical OTV's should be designed to have multiple redundancy in critical subsystems, such as to avoid reentry into the Earth's biosphere.
- Consideration of the use of an automatic ejection system for the waste payload during orbit transfer operations on the OTV is suggested.
- Consideration should be given to low-thrust systems (chemical, ion, and sail) for the advantage of providing the capability for a response to OTV failure, and thereby eliminating possible adverse effects caused by the failure if it were to reenter the Earth's biosphere.

Space Shuttle System

- Consideration should be given to improving Space Shuttle reliability for waste disposal missions.

Operations

- Launch constraints should be instituted so that if dispersion predictions are such that significant human populations could be affected by an accident, the launch would be postponed. This would be done regardless of launch site chosen.
- A remote launch site (island or platform) with minimal land over-flight, during the first and subsequent orbits, would minimize the risk to man. Trades between considering first and subsequent orbits as most critical need to be evaluated.
- Adequate safeguards must be assured against intrusive acts of man.
- Provisions should be made for fast-response recovery teams, should reentry of the payload occur.
- A lunar waste disposal concept should provide for controlled soft landings at a given site and burial operations of the waste (automated or manned).
- Trajectories for the disposal mission should be chosen to minimize the probability of Earth encounter, over a time period such that the waste package becomes relatively less hazardous.

4.6 Political and International Implications

With the expansion of national and international activities in space, the nations of the world have seen fit to develop various conventions, treaties, and other multinational instruments to guide the use of space so as not to preclude its use by others and to minimize the use of space as a staging area for possible acts of aggression against other nations. The implications of these various conventions and treaties on the possibility of using the Space Shuttle or another vehicle for space disposal of high level radioactive waste (HLW) present a very real and complex set of issues. In this preliminary evaluation possible areas of issue or concern were identified from the treaties. No attempt could be made to study the body of legal treatises and international rulings that to date have applied to this area of concern.

NASA Headquarters Code I (B. Zook) and Code G (G. Mossinghoff) were contacted in the course of evaluation. Each expressed his opinion regarding the complexity of the issues, the depth of available precedent information, and most importantly the need for a thorough legal evaluation of the ramifications to the use of space for HLW disposal.

4.6.1 Existing Treaties and Implications

The following multinational treaties, conventions, and agreements currently in force and subscribed to by the U.S. have bearing upon the use of space for HLW disposal.

- "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space Including the Moon and Other Celestial Bodies" (1967)
- "Convention on International Liability for Damage Caused by Space Objects" (1972)
- "Agreement on the Rescue of Astronauts, the Return of Astronauts, and The Return of Objects Launched into Outer Space" (1972)
- "Convention on Damage Caused by Foreign Aircraft to Third Parties on the Surface" (1952).*

*U.S. Federal Aviation Administration does not consider the Shuttle Orbiter an Aircraft (G. Mossinghoff, NASA Headquarters, Code G, Personal communication, June, 1977).

These documents suggest the following issues which must be thoroughly explored in this early decision-making phase:

- Accident liability
  - — on Earth
  - — to other space objects
  - — on space bodies
- Exclusive use
  - — of the Moon surface
  - — of areas of outer space
- International program base
  - — source of HLW waste
  - — launch/landing sites
  - — processing sites
  - — mutual assistance in space
  - — use of the sea
- Weapons of mass destruction in orbit.

The scope of these issues is mainly related to accident situations rather than routine operations of a manned space vehicle delivering contained waste to a designated place in outer space. If a failsafe system cannot be assured then the issues of liability must be considered. Should ultimate disposal sites on celestial bodies such as the Moon be chosen, accidents resulting in contamination may be considered exclusive use under the terms of the Treaty on Outer Space. This must be considered in depth in future studies.

The possibility that the delivery of containerized HLW to outer space may be considered a "weapon of mass destruction in orbit" is another issue which demands careful study. Much relevant written material detailing what does and does not constitute such an action is available and should be reviewed before this issue area can be either dismissed or dealt with.

4.6.2 International Cooperation

As the use of nuclear power extends to other countries of the world, each of these countries will have nuclear waste which must be managed in some fashion. Currently, the nations of Russia, China, United Kingdom, France, West Germany, and Canada, as well as the United States have significant quantities of nuclear waste that require management for long-term storage and/or disposal. By the year 2000 it can be anticipated that Japan, Brazil, Australia, and Iran will have sufficient nuclear wastes to join this group. Other "nuclear power" countries, e.g., India, Israel, will have smaller quantities of waste which may be disposed of through another country's system or retained at least temporarily in above-ground storage.

Before a realistic assessment of the international implications can be made, the degree to which international cooperation is desired in this program must be outlined. Potential interactions include internationally-derived nuclear waste, internationally-derived processed wastes, international funding, non-U.S. launch facilities, or high seas launch facilities. The International Atomic Energy Association in Geneva, Switzerland could provide the interface for international aspects when realistic alternative national/international programs have been defined.

4.7 Intrusive Acts of Man

Planning against intrusive acts and implementing safeguards from both external and internal threats to the space-based nuclear waste disposal operation is a critical area of overall program planning. One action on the part of a deranged individual or unfriendly group could unravel the framework of operations safety and systems integrity which characterize the nuclear waste disposal effort. Such an act, successfully conducted, could result in severe environmental consequences (local and/or global). In the least case, even if such an act were not successful, it could cause sufficient critical political attention to be focused as to place the entire program in jeopardy. In this section, three aspects of the intrusion problem are discussed: the types of people/groups which are potential threats to the program, the deliberate actions both external and internal to the operation which are possible, and safeguards which should be implemented to prevent intrusive acts, and thus reduce the probability of environmental impact.

4.7.1 Need To Protect Against Certain Types of Individuals/Groups

There are four general classes of aggressors which represent a potential threat to the nuclear waste disposal operation: the mentally deranged, extortionists, terrorists or militant groups, and unfriendly nations.

The mentally deranged individual represents the least clearly defined threat because of the irrationality of his possible actions. These actions are likely to be motivated by internal psychological conflict resulting in an act of revenge (although the object of revenge may be only loosely connected with the cause of the conflict), an act to gain attention, or other similar acts. The threat from a deranged individual exists in proportion to the resources available to the individual and his degree of access to the operation. The tendency of the deranged individual would most likely be to act alone.

The extortionist will engage in intrusive activities that have monetary potential. Threat to carry out some action of destruction unless a ransom is paid is a typical example. The demand is likely to be preceded by a demonstration of believability that the threat can be carried out. Typically, the extortionist does not want to carry out the threat, but will increase the believability of his destructive intentions by degrees until the ransom is paid. If the threat is real, the extortionist may arrange for it to be carried out in the event he is double-crossed and he will retain control of the threat until his personal safekeeping is assured. Acts of extortion are envisioned to be conducted by a small group of individuals rather than by a single individual acting alone.

The terrorist or militant group is usually acting out of disillusionment or dissatisfaction with an existing political/sociological/economic system. Though the goals of such an organization could include revenge or extortion they are more likely to involve non-monetary goals such as the release of political prisioners, redistribution of wealth, or publicity for a particular ideology. If truly committed to the ideology, the militants could be expected to fight to the death, and undergo severe military-like training and discipline for the operation. The terrorist/militant group may or may not want to commit the act threatened; however, this class of intruder is more likely to carry out the threat than would the extortionist.

The final class of intruder is an unfriendly nation, and actions by this class would be an act of war if carried out. It is beyond the scope of this report to consider the consequences of such

an action, though it can be noted that the act would most likely be well planned, conducted with expert and military precision, and backed by the full resources of the aggressor nation. It should also be noted that an unfriendly nation might support or disguise its intent as the action of a deranged individual, extortionist, or terrorist group. Political power would be the primary motivation.

4.7.2 Types of Deliberate Actions to Protect Against

The range of actions which could be conducted by the types of individuals/groups discussed above is extensive and includes theft and varied degrees of destruction both external and internal to the operation in all phases of terrestrial handling and transportation, launch and space operations.

External to the operation, theft and destruction are considered the principal intrusive acts. Theft is most likely to occur during Earth transport or storage once the nuclear waste has been reduced to a high level state. Theft is likely to be conducted by the extortionist or terrorist group, so that the high level waste can be used as a threat to demand monetary or other ransom. An unfriendly nation without access to nuclear materials may want to acquire the waste for armament purposes.

Key points of vulnerability exist once the waste is processed and before it is contained in the large shipping vessel, and again when the waste is removed from the shipping vessel and prepared for Shuttle flight. During ground transport, the large vessel makes theft difficult. Theft during space operations is extremely difficult but possible with such systems as satellite intercept/retrieve vehicles. However, a country with the sophistication to employ these methods for theft would most likely have nothing to gain.

Destruction could be envisioned primarily as the action of a deranged individual, or an unfriendly nation, though it could also be an act of retaliation or publicity by a terrorist organization. Destruction could take place at any phase of transport, ground operations, launch, or space operations. Destruction at certain altitudes during launch, or while transporting near a populated area could have severe impact if the destructive weapon caused aerial or aqueous dispersion of high level waste (see Section 4.4). Armor piercing projectiles and certain guided missiles are potential weapons for destruction as well as the use of planted explosive devices. Other weapons less likely to be employed include lasers, particle beam weapons and satellite destroy systems.

In addition to external acts, the potential for intrusive activities extends to the internal operations of the nuclear waste disposal program. It is possible that a deranged individual could be part of the program personnel, or that a militant group or unfriendly nation has managed to bribe, blackmail, or extort personnel or infiltrate the operation with an agent. Three system areas are principal areas of vulnerability; software, the STS/OTV, and the nuclear cocoon and its systems. Software systems control launch and space operations, and tampering is possible for theft or destruction. As an example, the OTV might be programmed to a reentry orbit once the protective cask was removed, and held there pending payment of an enormous ransom. All hardware systems are subject to tampering or placement of explosive or interference devices. If sophisticated expertise and internal assistance were acquired by an aggressive third party, severe consequences could result.

4.7.3 Necessary Safeguards

The range of potential aggressors and various motivations of the acts discussed above suggest several areas which require safeguards. These include:

(1) Waste processing facility

(2) Transport to launch preparation facility

(3) Launch preparation facility and launch site area

(4) Personnel

(5) Hardware and materials checkout

(6) Refurbishment operations

(7) Software and mission planning

(8) Complexities introduced by remote island launch site.

Security at the high level waste processing facility is required to prevent theft or tampering with the transport containment vessel, including implantation of explosive devices. The transport vessel and transport vehicle would be given a thorough systems check and search for devices and then be secured from unauthorized personnel.

It is recommended that the plans for transport to launch site be released on a need-to-know basis only, and the non-U.S. transport be carried out with limited military escort, backed by contingency forces. The object of the military backup would be to mobilize a defense instantaneously should an incident develop on the high seas. The containment vessel used in transport will require protection from limited ballistic weapons and high pressures generated if it should sink in the ocean.

It is recommended that the launch preparation facility and launch site area be treated as a secure base of operations. All hardware elements and materials entering the operation should be checked for tampering or implanted devices especially since certain components and equipment will enter the system from a variety of unsecured facilities, such as various manufacturing operations. Personnel will require careful screening and periodic review, with emphasis on those personnel responsible for systems verification, software, and similar points of vulnerability. Procedures to oversee refurbishment operations, systems checkout, software, and mission planning will have to be developed with security from intrusive acts as a primary objective.

The security of a remote island base compared to KSC and the added complexity of transport of high level waste via the ocean are of major importance in the consideration of intrusive actions and necessary preventative measures. On the island site, assuming a non-military multinational undertaking, personnel screening would be very difficult, and infiltration by militant groups or unfriendly nations could be a possibility. Also, depending on the ease of entry onto the island, terrorist group attack could be a potential threat. Increased transport of materials and hardware will increase the time available and opportunity for tampering or device implantation. Proximity to uncooperative nations could stir political difficulty within the global political framework because of undertaking a potentially dangerous activity in the proximity of another country. Assuming these problems could be resolved, the aspect of ocean transport introduces new variables into destruction and theft scenarios. If destruction were to occur during the transport, ocean dispersion of the nuclear material could

create problems. If the ship were destroyed and the container not found, the consequences of container migration and eventual corrosion might cause problems for future generations. The theft problem is intensified for several reasons. First, the transport time is increased. Second, the potential for stealing the entire ship and either removing the waste or moving it to a densely populated area while holding the ship's crew hostage is a possibility. Third, a military escort would be significant and expensive operation for a lengthy ocean voyage. In conclusion, the ocean transport of high level waste to a remote island site would be expected to introduce significant complexity into the nuclear waste disposal operation.

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5.0 SUMMARY AND CONCLUSIONS

The preliminary effort in identifying requirements which are unique to support the nuclear waste disposal in space concept and which might impact the nuclear fuel cycle, as discussed in Sections 1 through 4 of this report, led to the following:

- There are significant uncertainties regarding the Nation's nuclear policy that will affect nuclear waste management.
- It is difficult to define the optimum waste form and nuclide mix for space disposal assuming present technology, but it is likely to be different from that for terrestrial.
- There are no apparent technical reasons why the mixes cannot be prepared.
- The possibility of partitioning Zr and Mo out of the space disposal fraction offers advantages of weight reduction and the prospect of using these materials in useful applications.
- The costs associated with the fuel processing and waste solidification for space disposal are not expected to be significantly different from those for terrestrial isolation.
- The cost of actual emplacement will likely be significantly greater for space disposal of waste than for terrestrial isolation, and may increase the safety of waste management.
- Internal fins for heat transfer will be required in the waste canister if a package with L/D = 1 is used to contain calcine waste.
- Major parts of the container and shielding package can be used for both ground and space transportation, within regulatory standards.
- Suitable state-of-the-art materials exist for the container and shielding.
- Canister designs can be developed which will withstand water impact.
- Nuclear criticality is not a problem with the waste package, except possibly for waste Mix No. 2.
- Normal operations do not impose any significant environmental impact to the Earth's biosphere beyond normal Space Shuttle and OTV operations.
- Use of a crater on the Moon as a disposal/storage site could preclude the use of that limited region of the Moon for other purposes.
- Hypothetical worst-case accidents, should they occur, are extremely serious.
- Disposal of all high level waste (Mix No. 1) in space is impractical because of environmental impact, energy requirements, and economic factors, and warrants no additional study.

- Launch rates required for Mix No. 5 (technetium alone) and perhaps Mix No. 4 (0.1% U + Pu, other actinides, and rare earths except Ce) can be reasonably handled at KSC.

- Mixes Nos. 2 and 3 would most likely require a remote off-shore launch site to be developed.

- Of the five accident types treated, the two most severe hypothetical accidents are (1) the on- or near-pad catastrophic failure with subsequent release of radioactive material and (2) the complete burnup on reentry.

- Political and international consideration of space disposal is a complicated and sensitive situation that needs to be dealt with accordingly.

6.0 RECOMMENDATIONS

In order for the space option to be viable, it is desirable for NASA and ERDA to jointly evaluate the desirability of pursuing the matter, and to establish an interface activity to define or recommend the fuel cycle and support facilities to incorporate the space option in the overall waste management system including the following:

- Additional feasibility studies are needed to explore available options and resolve unanswered questions. (NASA)*
- Analytical studies followed by experimental efforts on alternate waste forms should be pursued. (ERDA)
- NASA should consider incorporating part of the cocoon into the shielding and canister structure. (NASA)
- In-depth parametric analysis of the canister design and internal heat transfer members should be initiated. (NASA)
- Testing of structural properties for possible materials for canister shielding needs to be undertaken to permit their ultimate licensing and design activities. (ERDA)
- Study of a lunar storage/disposal site should be initiated, including consideration of manned and unmanned disposal operation, controlled soft landings and burial under the surface of the moon. (NASA)
- Because hypothetical worst-case results are so severe as a result of accidents during space transport, consideration should be given to design of the cocoon-container system to be able to withstand any environment while in the vicinity of the Earth's biosphere. (NASA)
- Launch constraint studies should be initiated. (NASA)
- More in-depth environmental studies should be initiated on the yet-to-be-defined worst credible cases and continued on the hypothetical worst cases. (NASA)
- A fault-tree analysis of the entire space disposal mission should be initiated as part of an overall risk assessment. (NASA)
- Suggested design and operational procedures, as discussed in the text, should be considered. (NASA)
- Discussions between Federal and international agencies should be initiated regarding the legal and political aspects of a space disposal activity. (NASA)
- Further study of intrusive acts and safeguards is required. (NASA)

*Parenthetic notation after each recommendation indicates prime agency responsibility.

7.0 GLOSSARY

Aneuploidy — Having an abnormal number of chromosomes

ANL — Argone National Laboratory

BEIR — Biological effects of ionizing radiation

Calcine — Oxidized HLW

CANDU — Canadian deuterium uranium reactor

Chromosomal trait — Hereditary characteristic transmitted by sexual reproduction of animals or plants

Cocoon — The reentry envelope for a nuclear waste payload, used while transported by the Space Shuttle

Curie — 3.7×10^{10} disintegrations per second

Cytogenic — Formation and development of cells

DOT — Department of Transportation

EPA — Environmental Protection Agency

ERDA — Energy Research and Development Administration

ET — Space Shuttle's External Tank

FRC — Federal Radiation Council

GEIS — Generic Environmental Impact Statement

GESMO — Generic Environmental Statement for the Mixed Oxide Fuel Cycle

GW_e — Gigawatts electrical

HAW — High level waste stream

HDEHP — Bis-(2-ethyl-hexyl) phosphoric acid

Heliocentric — Orbits around the sun (sun centered)

HLW — High level waste

HTGR — High-temperature gas-cooled reactor

IAEA — International Atomic Energy Agency

IBX, IBS, HA column — Solvent extraction columns

ICRP — International Commission of Radiological Protection

IRTS — Idaho Reactor Test Site

IUS — Interim Upper Stage

Kick stage — A propulsive stage which propels a payload to a different, higher energy orbit

KSC — NASA's Kennedy Space Center, Florida

LES — Lincoln Experimental Satellite

Liquidus temperature — Temperature at which first solid forms in a molten solution

LF_2 — Liquid fluorine

LH_2 — Liquid hydrogen

LMFBR — Liquid metal fast breeder reactor

LO_2 — Liquid oxygen

LWR — Light water reactor

MMH — Monomethyl hydrazine

MSFC — NASA's Marshall Space Flight Center

MT — Metric ton

MTU — Metric ton of uranium charged to the reactor

MWD — Megawatt day

MWd/MT — Megawatt days per metric ton (also MWD/T)

N_2H_4 — Hydrazine

N_2O_4 — Nitrogen tetroxide

NASA — National Aeronautics and Space Administration

NCRP — National Committee on Radiation Protection and Measurements

NEP — Nuclear electric propulsion

NPH — Normal parafin hydrocarbon

NRC — Nuclear Regulatory Commission

NSTL — NASA's National Space Technology Laboratory

ORNL — Oak Ridge National Laboratory

OTV — Orbit Transfer Vehicle

Pallet — The structure which supports payloads in the Shuttle cargo bay

PBAN — Polybqtadiene acrylic acid acrylonitrile binder for the SRM propellant mix

PCR — Payload changeout room

PNL — Battelle's Pacific Northwest Laboratories

Polyploidy XO — An organism with more than two sets of female chromosomes

R/hr — Unit of radiation dose rate, rem per hour

Rad — Radiation absorbed dose—one rad is the dose corresponding to the absorption of 100 ergs per gram of tissue

RE — Rare earths

Recessive trait — Genetic characteristic which is not expressed in offspring when other parent carries a dominant gene for that trait

Rem — Roentgen equivalent, man—is a measure of the dose of any ionizing radiation to body tissue in terms of its biological effect relative to a dose of one roentgen

Roentgen — One roentgen is defined as the amount of radiation that produces, in one cubic centimeter of dry air under standard conditions, ionization of one electrostatic unit of charge

Rpm — Revolutions per minute

RTG — Radioisotopic thermoelectric generator

SEP — Solar electric propulsion

SNAP — Systems for nuclear auxiliary power

Somatic — Pertaining to the nonreproductive cells, nongenetic

SPS — Solar power stations

SRM — Space Shuttle's Solid Rocket Motor

SSME — Space Shuttle's Main Engine

SSP — Solar sail propulsion

TBP — Tributyl phosphate

Type B packaging — A radioactive shipping container designuted by NRC/DOT

W — Watts

X-chromosome-linked trait — Sex-linked trait